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An Index and Guide to Robotics Research and Development in Canada

Robotics and Automation Laboratory,
Department of Mechanical Engineering,
University of Toronto

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Department of Mechanical Engineering
University of Toronto

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ADDENDUM TO

"An Index and Guide to Robotics Research and Development in Canada", ERB-978, page 177

Journal Papers

1. Shih, L.Y. On the elliptic path of an end-effector for an anthropomorphic manipulator. Int. J. Robot. Res. 3(1): 51-57; 1984.

2. Shih, L.Y. Automatic guidance of mobile robots in two-way traffic. Automatica, 21(2): 193-198; 1985.

3. Shih, L.Y. Co-ordinated movements to avoid collision of a twin-robot system. Appl. Math. Model. 9(5): 380-384; 1985.

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2. Shih, L.Y. Redundant anthropomorphic manipulator subject to a kinematic constraint. Proc. 1983 IEEE Int. Conf. on Systems, Man, and Cybernetics, December 1983 - January 1984. pp. 676-679.

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SUMMARY

This report is a guide and index to robotics research and development in Canada. The production of this guide has been initiated, and funded, by the National Research Council of Canada and it was prepared, under contract, by the staff of the Robotics and Automation Laboratory, Department of Mechanical Engineering at the University of Toronto (prime contractor) and the Ontario Robotics Centre, Peterborough, Ontario (sub-contractor).

Universities, colleges, industry and government agencies were invited to submit (in response to a questionnaire) data related to their past, present and future research and development work related to the area of robotics. The more important centres of activities were visited by member(s) of the team performing the study. The information gathered was processed to fit the purpose and the format chosen for presentation of results. Most of the information submitted was complete and conformed to the requirements of the study. Unfortunately, however, some centres did not deliver information in a suitable form and others did not respond at all.

The team conducting this study was impressed with the quantity and quality of robotics-related work being conducted across Canada. More importantly, it is felt that the potential which exists at some of the centres is considerable, approaching the level of world-class research centres.

It must be emphasized that the importance of robotics research warrants effective funding. The level of funding at this time reflects a lack of national concern. Other countries participating in the Joint Co-ordinating Forum on International Co-operation in Advanced Robotics support this area of activity more effectively and more substantially. The few bright spots reflecting world-recognized Canadian successes in both industry and academia must be particularly supported. In particular Canadian efforts in research and development in robotics must strive toward international recognition and the support must be adequate to make this possible.

1. INTRODUCTION

1.1 A Need for National/International Awareness of Canadian Robotics Research and Development Efforts

Increased activity in the areas of robotics and automation technology, spurred by economic and social incentives in the manufacturing and service industries, is the primary reason for the recent formation of numerous research and development centres across Canada. Although significant research, in terms of both quality and quantity, is being conducted at most of these centers, an inherent problem existed in identifying and learning of the work that is being undertaken.

In order to increase our research community's awareness of developments in the area of robotics on the national scale and to increase international awareness of Canadian developments, a guide to robotics research and development in Canada was needed. That guide should be a valuable reference to Canadian and international researchers interested in integrating their research activities and it should also assist researchers in their selection of future research areas. For the international community, a Canadian robotics research and development guide should indicate the direction and extent of robotics research within Canada and illustrate the advanced capabilities which we, as a nation, possess.

1.2 Production of "An Index and Guide to Robotics Research and Development in Canada"

The production of this index/guide was initiated by the National Research Council of Canada. A contract was awarded to the University of Toronto's Department of Mechanical Engineering's Robotics and Automation Laboratory (prime contractor) to prepare the index/guide with the co-operation of the Ontario Robotics Centre (sub-contractor).

1.2.1 Objectives

The objectives of the index/guide are as follows:

i) To increase the national research community's awareness of Canadian activities in robotics research and development.

The report will be of value to researchers in universities, government laboratories, industry and elsewhere in planning their on-going work and in using, to maximum advantage, the work of others. In addition, it will be a useful reference and guide to managers and technical personnel in industry for locating where robotics research and development is being undertaken in Canada, and to assess the nature and extent of this research work.

ii) To increase the international research community's awareness of Canadian activities in robotics research and development.

Canada is one of a number of countries participating in the Joint Co-ordinating Forum on International Co-operation in Advanced Robotics. The main purpose of this forum is to facilitate, through international co-operation, the development of advanced robotic systems for applications which will reduce the necessity for people to work in harsh, difficult or dangerous environments and increase the level of automation in industrial processes. Accordingly, the guide to robotics research and development in Canada will be useful in informing officials and researchers in other participating countries of the interest and capability which exist in Canada and in arranging, where appropriate, Canadian participation in joint projects which are currently in the planning stage.

1.2.2 Methodology

The responsibility for preparing the index/guide was divided between the University of Toronto - Department of Mechanical Engineering's Robotics and Automation Laboratory (UTME-RAL) and the Ontario Robotics Centre (ORC). UTME-RAL assumed responsibility for contacting and documenting the robotics research and development centres at Canadian universities (and colleges) while ORC was given responsibility for contacting and documenting research centres in the government and industrial sectors.

In the course of researching Canadian universities (and colleges), the following steps were taken. Initial phone contact was made with the centres through research contacts listed in [1] through [5]. Additional contacts were made with researchers known to the University of Toronto faculty involved in producing the index/guide (Section 1.2.3). In order to ensure that all universities were contacted, the commonwealth Universities Yearbook [6] was used. This book provided the names of the heads of the mechanical engineering, electrical engineering and computer science departments of all Canadian universities. Contact with these department heads then, usually, provided the name of the researcher(s) involved in robotics. Other contacts were obtained by collecting names of Canadian researchers from periodicals and books dealing with robotics research.

Contacts in the industrial and government sectors were obtained from a list made available by NRC and from contacts known to ORC's index/guide research team (Section 1.2.3).

Once phone contact had been made and the research/development had been deemed relevant, a questionnnaire package (see Appendix A) was forwarded to the appropriate person. In an effort to contact as many researchers as possible, a questionnaire package was produced which consisted of two questionnaires (one personally addressed to the initial contact and one unaddressed) with a notice advising distribution within the institution (i.e., different department, etc.). In all, 54 questionnaire packages were sent by RAL to contacts in 32 universities and colleges and 31 packages were sent to industrial/government contacts by ORC (see Appendix B).

Following distribution of the questionnaire, an extensive phone follow-up was carried out. The first phase of this follow-up determined whether the questionnaire had been received and requested its prompt return. The second phase was used to elaborate on questionnaire responses where required. The third phase was used to retrieve late responses. This process resulted in 71 responses (48 educational and 23 industrial/government) being received out of 85 questionnaires sent.

While several complete, informative, well-organized responses were received, a good number were lacking all the information necessary for a complete entry within the guide. This may have been due either to an honest lack of activity at this time or to a lack of time required to produce a complete questionnaire response. In any case, the data presented herein is as accurate and complete a representation as could be produced based upon information gathered from questionnaire responses, site visits and telephone interviews.

Sites known to have major robotics research and development effort, or whose questionnaire responses indicated such, were visited by members of the guide's research team. It was felt that visiting the sites in order to gather the necessary information was the most productive and efficient method. Typically, much more can be learned about the individual researchers, the research progress, and the centre's capabilities through a visit than could be obtained via a questionnaire or telephone interview. While it was either impractical or unwarranted to visit all sites, many were visited. In the case of university sites, these visits were performed by the University of Toronto's faculty members. Government and industrial sites were visited by members of ORC's research team (Section 1.2.3). A list of sites visited (arranged geographically) is presented below.

Robotics Research and Development Sites Visited

Universities

1)	University of British Columbia	Department of Mechanical Engineering, Department of Electrical Engineering, Department of Computer Science
2)	University of Manitoba	Department of Mechanical/Industrial Engineering (Industrial Automation and Simulation Laboratory), Department of Electrical Engineering
3)	University of Waterloo	Department of Systems Design Engineering (Pattern Analysis and Machine Intelligence Group (PAMI Group))

4)	McMaster University	Department of Mechanical Engineering, Department of Electrical Engineering (Centre for Flexible Manufacturing Research and Development)
5)	Carleton University	Department of Mechanical/Aeronautical Engineering (Centre for Advanced Studies in Computer Aided Design (CASCADE), Robotics and Control Systems Laboratory (RCSL))
6)	Concordia University	Department of Mechanical Engineering (Centre for Industrial Control)
7)	McGill University	Department of Electrical Engineering (Computer Vision and Robotics Laboratory (CVaRL))
8)	University of Toronto	Department of Mechanical Engineering (Robotics and Automation Laboratory (RAL)), Department of Electrical Engineering, Department of Computer Science, Department of Industrial Engineering
9)	University of New Brunswick	Department of Mechanical Engineering, Department of Electrical Engineering, Department of Computer Science

<u>Industry/Government</u>

1)	Bata Engineering	
2)	Clay-Mill Technical Systems Ltd.	
3)	National Research Council	National Aeronautical Establishment (NRC/NAE)
4)	National Research Council	Division of Electrical Engineering (NRC/DEE)
5)	National Research Council	Division of Mechanical Engineering Systems Laboratory (NRC/DME)
6)	Ontario Robotics Centre	

7) Promatic International Ltd.

8) Spar Aerospace Ltd. — Remote Manipulator Systems Division (RMSD)

9) Vadeko International Inc.

10) Welding Institute of Canada (WIC)

11) Westinghouse Canada Inc.

12) Xenotech Systems Inc.

1.2.3 Index/Guide's Research Team

The personnel which comprised the research team are listed below.

	Name	Title
National Research Council of Canada		
	J. Scrimgeour	Senior Advisor - CAD/CAM, Robotics and Industrial Automation, Institute for Manufacturing Technology
	B. Pade	Project Administrator - Research Projects Support Office
Robotics and Automation Laboratory (University of Toronto, Department of Mechanical Engineering)		
Faculty	A.A. Goldenberg	• Associate Professor - Mechanical and Electrical Engineering • Robotics and Automation Laboratory Head • Principal Investigator
	R.G. Fenton	Professor - Mechanical Engineering
	K.C. Smith	Professor - Electrical Engineering
	J.K. Tsotsos	Assistant Professor - Computer Science
Staff	R.A.D. Wallace	Research Engineer - Robotics and Automation Laboratory

B. Benhabib	Graduate Student - Mechanical Engineering

Ontario Robotics Centre

I.A. Barrie	• Vice-President, General Manager • Principal Investigator
M. Lowe	Manager - Technical Services
M. Patrick	Manager - Applications Services
J. Hanright	Applications Engineer
B. Picard	Applications Engineer

1.3 How to Use this Guide

The "Index and Guide to Robotics Research and Development in Canada" is divided into five chapters in addition to references and appendices. Chapter 1 is an introduction to the guide. It outlines the necessity for such a guide, and explains how the data for the guide was obtained and presented. Chapter 2 is a technical chapter designed to clarify the definition of robotics research and development, and the areas addressed, and to outline the state of this research and development in Canada.

Chapter 3 presents the data on the research and development effort at educational institutes. This data was obtained by interpreting and/or by simply transposing the information provided by questionnaires. The institutions are divided into two groups as follows. Group 1 (Section 3.1) consists of universities/centres at which research and development directly applicable to robotics is being performed. This research deals with such areas as robot control, kinematics, dynamics, teleoperators, sensors, robotic vision systems, locomotion, etc. These areas are usually addressed by the Electrical, Mechanical and Industrial Engineering departments.

In addition, Group 1 contains robotics-related research which, for the purposes of this guide, has been classified as research which clearly has potential for robotic applications and/or which is obviously required for robotics of the future but which cannot be directly associated with present robotics technology. This robotics-related research is performed primarily within the realm of computer science and addresses computer vision (i.e., image analysis algorithms, biological vision simulation), artificial intelligence (AI), and computer automation.

Since it is difficult, or unfair, to rank the sites according to their research effort documented in the questionnaire responses (although a number of sites were visited thereby allowing these to be ranked if desired), the site entries are simply arranged geographically.

Group 2 (Section 3.2) consists of robotics training institutes. These are the colleges within Ontario at which robotics technology courses are taught (robotics training is also conducted in the universities). Although no robotics research is carried out within the colleges, they do have very good robotics facilities which, if they were to interact with the universities and industry, could be made available to these groups for research purposes.

The format for the university research site entries in Chapter 3 follows the scheme outlined in Figure 1 (ref. Appendix A - Questionnaire).

The data obtained by the Ontario Robotics Centre from private industry and the government sector is presented in Chapter 4. The two groups are presented separately with the latter covering both research laboratories associated with federal government departments and centres/corporations set up by the provincial governments.

Chapter 5 presents the closing remarks and conclusions.

To assist the user in obtaining specific data from the site entries in Chapters 3 and 4, cross-reference Table 1, which pertains to Chapter 3, and Tables 2 and 3, which pertain to Chapter 4, are provided.

INSTITUTE NAME

Department

Laboratory's Name

Address

Contact's Name
Contact's Phone

I) Site Data
Includes: Site's history and growth
Research facilities
Affiliation(s)
Source(s) and amount of funding
Fee structure for external service
Clientele
Expansion plans

II) Personnel Data
Includes: Names, Titles, Specializations of relevant personnel

III) Research Activities
Includes: Research areas
Principal objectives
Areas of specialization
Major accomplishments
Software developed or used

IV) Bibliography
Includes: Papers, reports, etc. which have been produced and/or published

(Depending on the amount of data to be entered, site entries may or may not employ sub-headings in order to clarify presentation).

Figure 1

Table I Cross-Reference of University Research and Development

PROVINCE:	British Columbia					Alberta			Saskatchewan	Manitoba
UNIVERSITY:	British Columbia			Simon Fraser		Alberta		Calgary	Saskatchewan	Manitoba
DEPARTMENT:	Mech. Eng.	Elec. Eng.	Comp. Sci.	Eng. Sci.	Comp. Sci.	Mech. Eng.	Psych.	Comp. Sci.	Eng./Comp. Sci.	Mech./Ind. Eng.
PAGE NUMBER:	34	36	38	51	52	53	54	55	57	59
RESEARCH AND DEVELOPMENT AREAS:										
Artificial Intelligence			X		X		X			
Computer Vision			X		X		X	X	X	X
Manipulation and Locomotion	X	X		X		X	X		X	X
Communication	X	X						X		X
Sensors										
Actuators										
Materials										
Productivity and Industrial Applications	X								X	X

Table 1. Cross-Reference of University Research and Development (Cont'd)

PROVINCE:	Ontario										
UNIVERSITY:	Carleton			McMaster	Queen's	Toronto				Waterloo	Western
DEPARTMENT:	Mech. Eng.	Comp. Sci.	CASCADE	Eng.	QUEL	Mech. Eng.	Elec. Eng.	Ind. Eng.	Comp. Sci.	Syst. Des. Eng.	Eng. Sci.
PAGE NUMBER:	63	65	66	68	71	77	95	97	98	109	113
RESEARCH AND DEVELOPMENT AREAS:											
Artificial Intelligence		X			X				X	X	
Computer Vision				X	X		X	X	X	X	
Manipulation and Locomotion	X		X	X	X	X	X			X	
Communication	X		X	X	X	X	X		X	X	X
Sensors					X	X					
Actuators											
Materials											
Productivity and Industrial Applications				X		X	X	X		X	

Table 1. Cross-Reference of University Research and Development (Cont'd)

PROVINCE:	Quebec									
UNIVERSITY:	Concordia	Ecole Polytechnique		McGill		Montreal	Quebec à Trois Rivieres	Sherbrooke	Tech. Sup.	
DEPARTMENT:	Mech. Eng.	Mech. Eng.	Elec. Eng.	Mech. Eng.	Elec. Eng.	I.R.O.	Eng.	Mech. Eng.	Eng.	Auto. Prdn.
PAGE NUMBER:	114	119	120	121	128	149	151	153	155	156
RESEARCH AND DEVELOPMENT AREAS:										
Artificial Intelligence					X					
Computer Vision					X	X				X
Manipulation and Locomotion	X	X	X	X	X	X		X		
Communication	X		X		X				X	
Sensors								X		
Actuators				X						
Materials										
Productivity and Industrial Applications					X		X			

Table 1. Cross-Reference of University Research and Development (Cont'd)

PROVINCE:	New Brunswick	Nova Scotia	
UNIVERSITY:	New Brunswick	Tech. University	
DEPARTMENT:	Eng.	Mech. Eng.	Ind. Eng.
PAGE NUMBER:	157	160	161
RESEARCH AND DEVELOPMENT AREAS:			
Artificial Intelligence			
Computer Vision			
Manipulation and Locomotion	X	X	
Communication			
Sensors			
Actuators			
Materials			
Productivity and Industrial Applications	X		X

Table 2. Cross-Reference of Government Research, Development and Applications

PROVINCE:	Alberta	Ontario		
FACILITY:	Alberta Research Council (ARC)	Atomic Energy (AECL) Chalk River Labs (CRNL)	Energy, Mines, Resources (EMR) Ctr. for Min. & En. Tech. (CANMET)	Nat'l Res. Council Nat'l Aero. Est. (NRC/Aero)
PAGE NUMBER:	170	171	173	176
APPLICATION:				
Automotive				
Education				
Manufacturing	X			
Mining			X	
Space				X
Welding				
Hostile Environment		X		X
RESEARCH AND DEVELOPMENT AREAS:				
Robotics Control				X
Man-Machine Interface				
Sensors and Vision Systems				X
Manipulator Gripper and Wrist Design				X
Applied Artificial Intelligence				
Systems Architecture				
Applications Development	X	X	X	X

Table 2. Cross-Reference of Government Research, Development and Applications (Cont'd)

PROVINCE:	Ontario				Quebec
FACILITY:	Nat'l Res. Council Div. Elec. Eng'g (NRC/DEE)	Nat'l Res. Council Div. Mech. Eng'g (NRC/DME)	Ont. Hydro	Ont. Robotics Centre (URC)	Centre de Rech. Ind. du Quebec (CRIQ)
PAGE NUMBER:	175	178	180	181	183
APPLICATION:					
Automotive				X	
Education				X	
Manufacturing	X	X		X	X
Mining				X	
Space	X				
Welding			X	X	
Hostile Environment			X	X	
RESEARCH AND DEVELOPMENT AREAS:					
Robotics Control	X	X	X		
Man Machine Interface	X	X		X	
Sensors and Vision Systems	X	X	X		
Manipulator Gripper and Wrist Design	X				
Applied Artificial Intelligence	X				
Systems Architecture	X		X		
Applications Development	X	X	X	X	X

Table 3. Cross-Reference of Industrial Research, Development and Applications

PROVINCE:	British Columbia	Saskatchewan	Ontario				
COMPANY:	Robotic Syst. Int'l (RSI)	Horizon Robotics	Bata Eng'g	Clay-Mill Tech. Syst.	CRS Plus	Diffracto	Magna Int'l
PAGE NUMBER:	186	188	189	190	191	192	193
APPLICATION:							
Automotive				X		X	X
Manufacturing	X	X	X	X	X	X	
Mining	X						
Space							
Subsea	X						
Welding							
Education	X	X					
Hostile Environment	X						
RESEARCH AND DEVELOPMENT AREAS:							
Robotics Control	X				X		
Man-Machine Interface	X	X					
Sensors and Vision Systems	X					X	
Manipulator Gripper and Wrist Design		X					
Robot Design				X	X		
Locomotion	X						
Applied A.I.							
Systems Architecture	X						
Applications Development	X	X	X	X	X	X	X

Table 3. Cross-Reference of Industrial Research, Development and Applications (Cont'd)

PROVINCE:	Ontario						Quebec	
COMPANY:	Promatic Int'l	SPAR Aero. (RMSD)	Vadeko Int'l	Welding Inst. Can. (WIC)	Westinghouse Canada	Xenotech Syst.	Servo Robot	Welding Inst.
PAGE NUMBER:	194	195	197	198	199	200	201	202
APPLICATION:								
Automotive	X	X	X	X			X	
Manufacturing		X	X	X	X		X	X
Mining			X	X				
Space								
Subsea								
Welding				X			X	X
Education					X			
Hostile Environment		X	X					
RESEARCH AND DEVELOPMENT AREAS:								
Robotics Control		X	X	X			X	X
Man Machine Interface		X	X				X	
Sensors and Vision Systems		X		X		X	X	X
Manipulator Gripper and Wrist Design		X	X					
Robot Design								
Locomotion								
Applied A.I.		X						
Systems Architecture			X					
Applications Development	X	X	X	X	X	X	X	X

2. ROBOTICS RESEARCH AND DEVELOPMENT

2.1 Defining Robotics Research and Development

Robotics research and development encompasses many engineering and applied science disciplines, primarily in electrical and mechanical engineering and computer science. In an attempt to filter the more relevant material and provide a systematic method of classification, specific areas of research and development had to be identified.

References [7] to [10] provide a useful guide to classifying robotics research and development. Based on these references and on a consensus of opinions (National Research Council and University of Toronto [11]) a list of areas to be addressed in this report was identified and included in the questionnaire (Appendix A). On the following pages, a brief overview of areas of robotics research and development is presented as an attempt to provide some definition to this diverse field.

In April 1980, a workshop sponsored by NSF and attended by many well-known experts in the field of robotics was held to identify the advanced scientific knowledge which is needed to provide a firm foundation for robotics. The results of the workshop were published in [7]. The focus was on fundamental knowledge, not applications-oriented knowledge as may be proposed by industry.

A robotic system is described in [7] as one capable of receiving communication, understanding its environment by the use of models, formulating plans, executing plans, and monitoring its operation. Based on [7] to [11], the following seven domains of robotics research and development have been identified: i) artificial intelligence, ii) manipulation and locomotion, iii) communication, iv) sensors, v) actuators, vi) materials, and vii) industrial applications. Each domain is briefly described below.

i.a) Artificial Intelligence

In the context of robotics, artificial intelligence is concerned with the automation of the programming task, or with tasks that cannot be pre-programmed, i.e., those that require intelligence. These aspects of robotics research are receiving much attention at the major research laboratories throughout the world, although very little in the way of practical application has emerged from the research at this time.

The components of intelligence that one would expect to be present in an intelligent machine may include:

- domain and common sense knowledge, and its representation
- a capacity to learn or adapt
- inference, problem-solving and planning capability
- the ability to direct the acquisition of sensory input
- the ability to understand and integrate sensory input
- natural language discourse capability
- the ability to perceptually guide behaviour
- locomotion

It would be unrealistically optimistic to think that the creation of intelligent machines that adequately deal with each of these aspects is near. It should also be clear that the above definition is not a complete one and, in fact, each of the topics contain many sub-topics of importance.

The solving of a problem by an intelligent machine may be thought of as an exercise in the transformation of problem representation, from a goal-oriented statement of the problem (such as "Put together the parts that form this widget"), to the exact sequence of manipulator motions that are required to execute the task. These problem decompositions involve traditional AI activities, such as problem-solving and planning, knowledge representation for the problem domain, and conflict resolution. They involve the interpretation of visual input and the ability to react to "surprises" in the visual input. A potential solution must then be transformed into manipulator commands using kinematic relationships. Control is crucial at all levels of these activities.

Note that it is not necessary, indeed for many reasons it is not even desirable, for each of these activities to be defined in the same formalism, for example mathematics. An appropriate formalism for each must be discovered and used.

i.b) Computer Vision and Artificial Intelligence

The field of Artificial Intelligence involves each of the aspects of intelligent machines stated previously. However, the sub-area of AI that is immediately relevant for robotics deals with understanding sensory input, Computer Vision in particular.

Computer Vision research and development concentrates on how to design and implement machines that can appropriately solve problems that deal with visual input. The great bulk of computer vision research has concentrated on the interpretation of passive input. It should be clear that active sensors such as laser rangefinders, light stripe illumination, ultrasound and others, are extremely useful in specific situations for robotics systems. However, the analysis of this type of "visual" input is usually not included under the computer vision umbrella.

Computer Vision research can be roughly divided into two major fields of activity, and although this division is not altogether a correct one, it is useful. The first category is loosely referred to as High Level Vision, sometimes also called Attentive Vision or the Cognitive Level of Vision. Researchers in this area concentrate on how to piece together visual information into descriptions of scenes that involve labelling of objects, inferring spatial relationships among objects, and relating what is seen to what is known about a problem domain. The second major area of activity is Low Level Vision, or Early Vision. Here, researchers are concerned with how to extract meaningful pieces of visual information from an image or image sequence such that those pieces of information can then be utilized by the high level vision component. These meaningful visual tokens include colour

information, depth through stereo information, motion, intensity discontinuities, texture, reflectance, and others.

It should be clear that although the above dichotomy is a convenient one, it by no means reflects the reality of computer vision systems. In fact, there is much interplay and communication between the High and Low levels of visual information processing. Roughly speaking, the state-of-the-art in these endeavours is the following. For tightly constrained application domains, Low Level Vision techniques can satisfactorily deal with the information extraction phase. Simple matching can then take the place of High Level Vision. In both Low and High Level Vision, there are many important research issues to be addressed, and much active work is taking place in Canada in both of these areas.

ii) Manipulation and Locomotion

A system that transmits forces in a predetermined manner in order to accomplish specific objectives is considered a machine. A system whose principal function is to transmit motion is a mechanism. A robot is an open-loop mechanism (manipulator). Kinematics is the study of motion in mechanisms (it includes analysis of displacements, velocities and accelerations and synthesis of mechanisms to produce specified types of motion). Dynamics is the study of forces and torques in systems that evolve with time (including the analysis of inertial effects).

Kinematic design involves choosing the structural parameters which relate adjacent joints and the gripper of the robot. Kinematic control methods (direct and inverse) are needed to coordinate the motion of the robot through the functional interdependence between the manipulator, the gripper, and the work space (environment). Robot kinematics is also studied from the point of view of optimal path planning and collision avoidance.

Kinematically redundant robots is another topic of importance for collision avoidance and singularity management. It covers the geometry of systems having multiple arms and the determination of the number of degrees-of-freedom (DOF) and how they should be distributed.

Another area of research concerns high speed manipulation which requires light-weight robots with structural flexibility. Substantial research is needed on dynamic modelling of flexible robotic systems and efficient solutions of the governing equations. Work on understanding the functional dependence between robotic performance and structural parameters is also important. Performance evaluation entails the accuracy, repeatability and reliability of robots.

The control function distinguishes robotics from pure artificial intelligence [8]. Relevant work is performed in combining system theoretic approaches with advanced methodologies. Generalization of concepts such as pattern recognition, image analysis, decision making, learning and system properties (theorem proving) is required for autonomous robots. Modern control theory is applicable to areas such as nonlinear control, adaptive

control, robust control and distributed computation. Work is also required in the theory of hierarchical control of distributed systems.

In the area of real-time control, integration of contact and non-contact sensors and man-machine interface are areas of intensive research.

There is need for the formulation of interpretation, the mapping between observations and object models which includes predictions and descriptions. Predictions are maps from models to observations. Descriptions are maps from observations to models.

Other developments of importance include: control of flexible link robots, design and control of dexterous multi-finger grippers with sensors (particularly touch sensors), and mobile robots which are suitable for teleoperative and autonomous operations.

Locomotion (mobility) of systems can be classified according to their kinematics, their means of propulsion, and the environment in which they must function. Research is required to determine under what conditions wheels, legs, loops, tracks, balloons, or screws are the best choice. New results in supervisory control might help to optimally partition the tasks between the operator and the teleoperated machine. A related research area is the automatic planning for navigation of mobile robotic vehicles. Improvements in actuator efficiency and weight are important issues. Static and dynamic stability over one cycle of locomotion is also a major research area.

iii) Communication

Man-machine communication is currently performed by specifying positions of the arm and creating programs which run a sequence of tasks. The increasing number of statements required by these programs for handling contingencies necessitates research to develop methods for automatically checking robot activities and for initiating corrective action if required. Research is focusing on developing high-level languages that incorporate geometric modelling systems and large data bases. Related work is being performed on developing methods for easy man-machine interface and for debugging sophisticated robot programs.

Unified engineering data bases which describe the physical and volumetric properties of objects are useful for robot programming. Off-line simulation of robot motions verifies collision free paths and considerably reduces the computational time spent during on-line teaching of the robot via remote control devices. Further research is needed to simulate contact phenomena using sensory information and to fit objects together in the model data base to compensate for variability.

The coordination of complex robots will most likely benefit from a better understanding of modular hierarchical structures. The properties of adaptation and learning should be exploited. The use of a microprocessor based joint control system is almost an automatic decision. Research on distributed processing and parallel bus structures is necessary for developing advanced robots. Research on software based controllers for control as

compared to hardware based controllers is currently being addressed. Related research is carried out on real-time interfacing with sensors, error detection, consistency checks, failure analysis routines and work-around routines for rapid fault detection, fault isolation and back-up operation. Research is also focusing on developing fail-safe and fail-operational robotic systems.

iv) Sensors

A sensor is a transducer used to measure a variable which is relevant to control activities. The types of sensors used today in industrial robotics include: contact sensors such as force and tactile sensors, and non-contact sensors such as vision, and proximity sensors. Robot vision might be considered as a process with four interactive stages as follows: 1) enhancement, which produces an accurate image; 2) segmentation, which decomposes an image; 3) feature extraction, which provides size and shape information; and 4) template matching, which is used to make decisions about objects.

Contact sensors can be used to direct contact, monitor and guide operations, and confirm data from non-contact sensors. There is a need to improve the performance of existing vision sensors, providing higher resolution, improved pixel quality, better lenses and fast focusing techniques. More work is needed on range sensors and on the corresponding problem of stereo vision.

Current arrays of touch and force sensors suffer from coarse resolution, low-speed and an excessive number of communication and control lines. Research is focusing on developing high resolution, compliant, two-dimensional arrays and integrating these with local microprocessors. As with the development of other sensors, new devices such as acoustic and temperature sensors are also being considered.

Research is needed to more effectively use sensing data by searching for a good set of language primitives for obtaining and acting upon sensory information. Problems with "noisy" data may be addressed with the use of Kalman filters and statistical pattern recognition techniques. The role of models in creating new processing algorithms needs to be clarified.

The speed of data processing must be improved by investigating the use of special purpose hardware and efficient software algorithms. Parallel interfacing and multiple computer systems must be considered for high speed operation. Research areas like range accuracy and reliability are also important issues.

v) Actuators

An actuator is a motor that converts some form of energy into mechanical energy. In robotics, that resultant action is the mechanical motion that provides the power to move each joint axis. Robot actuator drives can be electrical, pneumatic, hydraulic, or some combination of these.

Electrical actuators (servo motors, stepping motors, linear solenoids, rotational solenoids) are fast, accurate and lend themselves to sophisticated

control techniques. However, they require gear trains for transmission of power which limit precision due to backlash in the gears. Research must be conducted on areas such as torque fluctuation, mechanical stiffness, gear backlash and gear wear, which are widely encountered in electromechanical drives.

The most popular form of drive system for large loads is hydraulic. A hydraulic actuator converts the force of high pressure hydraulic fluid into mechanical shaft motion. Hydraulic actuators offer accurate control, safety, and resistance to harsh environments; however, they tend to contaminate the work cell and are not suitable for high speed. Pneumatic robots, on the other hand, are limited to small loads, but can operate at high speeds. Pneumatic actuators are not accurate due to the compressibility of air, and leakage of air is a major concern. Related research is required on preventing air or hydraulic liquid leakage by developing newly designed connectors that withstand vibration, expansion and contraction.

The direct-drive arm concept which is currently being explored excludes all the torque converters, thereby considerably increasing the stiffness, accuracy and speed of the joints. Future research on joint actuator design should consider requirements such as high torque, light weight and compactness of motors.

Individual actuator performance is an important factor which determines, ultimately, the mechanical performance of multi-finger dexterous grippers. Therefore, electromechanical performance of the actuator systems must be given a high priority in future research on dexterous grippers.

vi) Materials

In many industrial applications the use of heavy robots leads to reduced productivity due to their slow performance. One possible solution is to incorporate lighter links; however, this may make them less rigid and may lead to excessive deflections of the end-effector.

Fiber-reinforced composites combine light weight with reasonably high stiffness but are prone to creep and aging problems. The physical properties of composite materials are superior to those of metals, improving performance and life specifications for high-speed robots. Such materials may also solve some of the problems encountered in high-speed operations, namely stiffness and vibration. However, there are still some major difficulties in designing fiber-reinforced composite links. These include: choice and layout of the fibers, inertia computations and actual manufacturing of the link. Research has to be pursued in developing and designing optimal links which utilize a variety of materials.

vii) Industrial Applications

The use of computer integrated manufacturing (CIM) systems incorporating robots is of paramount interest to industry. The potential effects of advances being made in computer-aided design (CAD) and computer-aided

manufacturing (CAM), as well as flexible manufacturing systems (FMS) will improve productivity of industries.

From an industrial point of view, the most important research areas are those which will enable robots to perform autonomously. In modern manufacturing systems, the robots are expected to perform tasks such as material handling, manufacturing, assembly, welding, tracking, testing and inspection. These tasks require a high degree of robotic intelligence.

A central problem with industrial robotic intelligence is that robots may have to be interfaced to existing information systems (data bases and sensors) and then be required to make decisions among a large number of alternative actions. The current trend towards the development of automated factories requires the usage of autonomous robots with minimum human supervision.

2.2 The State of Robotics Research and Development in Canada

2.2.1 Educational Institutes

The brief summary presented in this section was drawn from an evaluation of the publications and research activities of the various educational institutes. Specific interests, planned research and early work in progress is not reflected in the evaluation. It is natural to expect, and most questionnaires have underlined this, that broadening of research activities will occur; thus, a more general view of research work for each centre can be obtained from the material in Chapter 3. The material in this section only highlights work finished and/or substantially in progress.

Artificial Intelligence

Research in Artificial Intelligence, as it applies in the broader context of intelligent machines, is conducted at a variety of centres. The largest of the AI centres, and the one having the broadest scope, is within the Department of Computer Science at the University of Toronto. Other large AI centres are located within the University of British Columbia (Computer Science Department), Simon Fraser University (Computer Science Department), the University of Waterloo (System and Design Engineering), and McGill University (Electrical Engineering Department). The Simon Fraser and Waterloo groups are relatively young but have great potential for future research. Smaller groups of research people can be found at the University of Alberta (Department of Psychology), the University of Saskatchewan (Computer Science Department), the University of Western Ontario (Engineering Department), Queen's University (Computer and Information Science), the University of Ottawa, Carleton University (Computer Science Department), Concordia University and Dalhousie University. Note that not all of the groups mentioned above responded to the questionnaire.

Computer Vision

Relative to the rest of AI, there is an enormous amount of computer

vision activity in Canadian universities. The most important centres in this area can be found at: the University of British Columbia's Department of Computer Science, McGill University's Department of Electrical Engineering, and the University of Toronto's Department of Computer Science. These three groups have received international recognition for their research in the areas of Computer Vision and Artificial Intelligence, and these efforts form the Artificial Intelligence and Robotics Program of the Canadian Institute for Advanced Research. In each of these centres there are more than twenty (20) faculty, graduate students and staff members active in the area. A sampling of medium size (less than 10 but more than 3 people) activities, in computer science departments, are at: Simon Fraser University, the University of Ottawa, Carleton University, and Queen's University. Small activities (3 or fewer researchers) can be found at: the University of Alberta (Psychology Department), University of Calgary (Computer Science), the University of Western Ontario (Engineering Department), and Dalhousie University.

A notable result of the survey is the observation that no computer vision group within a computer science department at this point has formed a major robotics laboratory. There is an effort in this direction however at Queen's University.

Manipulation and Locomotion

Research work in this category covers issues related to kinematics, dynamics, control and design of robots. There are many centres across Canada (mainly Electrical, Mechanical and Industrial Engineering departments) where research has been performed for a number of years or where new operations have been, or are being established, thereby representing a new thrust in this direction.

The largest research centre is located at the University of Toronto, Department of Mechanical Engineering, Robotics and Automation Laboratory. The laboratory has a large research team (2 professors, 6 engineers, 15 graduate students), equipment (several robots, vision systems, CAD stations, computers, etc.) and a strong record of publications and industrial contracts. The main areas of research are kinematics, force control, design, mobility and articulated grippers (multi-fingered hand). Research is also performed within the Electrical Engineering Department at the University of Toronto in the areas of control of flexible arms, kinematics and dynamics.

A large research centre is also located at McGill University. This centre combines efforts from the Electrical Engineering Department (force control, identification, trajectory planning) and Mechanical Engineering Department (kinematics, trajectory optimization, dynamics). The McGill group is very large (several professors, full-time engineers, and at least 15 graduate students). Their equipment includes several robots, vision systems and computers. In addition, they have numerous publications in international journals to their credit.

Combining the efforts of both Electrical and Mechanical Engineering

Departments, the centers at the University of Toronto and McGill University are the largest in the country. The level of funding at the University of Toronto is near adequate, whereas McGill receives the largest financial support and is expected to increase its research productivity in the near future.

Continuously increasing efforts exist within the University of British Columbia's Mechanical Engineering (task space control) and Electrical Engineering Departments (teleoperators and control). Other active research groups are located within: the University of Alberta's Department of Psychology (pattern recognition), the University of Saskatchewan (hydraulic control, mobility, myoelectric arms), the University of Manitoba's Mechanical and Industrial Engineering Department (kinematics), McMaster University's School of Engineering (control, path planning), Queen's University's Electrical Engineering Department (adaptive control), Carleton University's Mechanical Engineering Department (kinematics, control), the University of Waterloo's Systems Design Engineering (control, pattern recognition), Concordia University's Mechanical Engineering Department (remote manipulation, control, mobility), the University of Sherbrooke's Mechanical Engineering Department (design, compliance), and the University of New Brunswick's School of Engineering (design, microprocessor control, adaptive control, NC control).

Smaller centres (i.e., one professor and several students) were recently established at Simon Fraser University (navigation of mobile robot), the University of Alberta's Mechanical Engineering Department, École Polytechnique's Mechanical Engineering Department (guided vehicles and control) and the University of Montreal (trajectory planning, multiple robot coordination).

Communication

Research work in this category covers issues related to programming (automatic, off-line), man-machine interface, real-time control, simulation (non-real-time and real-time), and image processing (control, sensory information).

The larger centers performing research in this category are located within: the University of British Columbia's Electrical Engineering (image processing, man-machine interface, integrated circuit design) and Mechanical Engineering Departments (automatic programming), the University of Calgary's Computer Science Department (simulations, real-time control), the University of Saskatchewan's Computer Science Department (simulations), the University of Manitoba's Mechanical/Industrial Engineering Department (simulation), McMaster University's School of Engineering (off-line programming, real-time control, simulation), the University of Waterloo's System Design Engineering Department (image processing), the University of Toronto's Mechanical Engineering (simulation, real-time control, tactile sensing) and Electrical Engineering Departments (man-machine, image processing of sensory information), Carleton University's Mechanical Engineering Department (simulation), Queen's University's Electrical Engineering and Computer Science Departments (image processing, tactile sensing), and McGill University's Electrical Engineering

(image processing) and Mechanical Engineering (simulation and sensing) Departments.

Smaller groups are active at the University of Western Ontario's Engineering Science Department (robot interface), Concordia University's Mechanical Engineering Department (simulation), and the University of Quebec's Mechanical Engineering Department (off-line programming).

Sensors

Research work in this category covers issues related to development of sensors (design, hardware and software for local data processing). The main research efforts are located within the University of Toronto's Mechanical Engineering Department (tactile sensing), Queen's University's Computer and Information Science Department (tactile sensing), and the University of Sherbrooke's Mechanical Engineering Department (instrumented remote center compliance).

Actuators

Research work in this category covers issues related to new means of actuation for robotics (theory, design and experimentation). Limited efforts have been identified within McGill University's Mechanical Engineering Department.

Materials

Research in this category covers issues related to light-weight structures, modular robots and new materials (composite) for robot structures. No work is being conducted within this area at the present time in Canada.

Productivity, Automated Manufacturing, Applications

Research work in this category covers issues related to Computer Integrated Manufacturing (CIM), Flexible Manufacturing Systems (FMS), CAD/CAM, simulation and optimization of processes and applications. Research is conducted at the following centers: the University of British Columbia's Mechanical Engineering Department (welding and forest industry application), the University of Saskatchewan's Computer Science Department (mining and agricultural applications), the University of Manitoba's Mechanical/Industrial Engineering Department (integration of automated manufacturing, discreet event simulation), McMaster University's Mechanical Engineering Department (FMS, welding and inspection applications), the University of Toronto's Mechanical Engineering Department (assembly in electronic component manufacturing, automatic instrumentation for nuclear applications, CAD/CAM and robot work cell integration), Electrical Engineering Department (FMS) and Industrial Engineering Department (FMS), the University of Waterloo's System Design Engineering Department (electronic equipment repair, inspection), the University of Quebec at Trois Rivieres (safety, PCB asembly, robotic tooling),

the University of New Brunswick's School of Engineering (CAD/CAM) and the Technical University of Nova Scotia's Mechanical and Industrial Engineering Departments (FMS, CAD/CAM).

2.2.2 Private Industry and Government Sectors

An extensive amount of robotics research and development is conducted in both the private industry and government sectors. Departments of the Canadian federal government operate research laboratories such as Atomic Energy of Canada Ltd.'s Chalk River Nuclear Laboratory (AECL/CRNL), Energy, Mines and Resources Canada's Centre for Mineral and Energy Technology (EMR/CANMET), and the National Research Council's National Aeronautical Establishment (NRC/NAE), Division of Electrical Engineering (NRC/DEE), and Division of Mechanical Engineering Systems Laboratory (NRC/DME). In addition, provincial governments have established research and development centres such as Quebec's Centre de Recherche Industrielle du Quebec (CRIQ), Ontario's Ontario Robotics Centre (ORC), and a facility set up by Alberta's Alberta Research Council (ARC). These government centres tend to finance most of the higher risk, long term research and development. The overall government objective is to complement industry research and to perform research and development that would not otherwise be performed, thereby contributing to the economic prosperity of Canada.

Private industry tends to focus its efforts on shorter-term research and development for immediate industrial applications or for projects financed by government and universities. Industry objectives are two-fold: to develop and to refine marketable products such as end-of-arm tooling and specialized grippers, and to provide advanced design engineering on a contractual basis to universities, government, and industry.

Recognizing the need to catch up to its foreign competition by making the transition to automated manufacturing systems, industry has made significant developments in robotics technology. The physical facilities for robotics research and development includes some of the most advanced laboratories in North America. Many companies specializing in automated systems have the in-house capability to design, develop and to produce a complete robotics system. Moreover, the willingness of the private, government and educational research sectors to cooperate on research and development projects results in the sharing of physical and informational resources.

The relatively recent arrival of robotics technology as a major economic force has resulted in the establishment of many robotics consulting companies within the last few years. Some are specialized spin-offs from older companies, and many of the smaller companies included in this directory started operation with NRC funding within the last four years. On the other hand, some of the companies have been in operation for decades and robotics is only one of their business interests.

The scope of robotics research and development in Canada includes projects ranging in size and effort from the development of a specialized single-purpose automated device to improve an existing manufacturing system,

to a long-term program to automate the complete underground hard-rock mining operation. State-of-the-art research is being conducted in adaptive control systems employing sensor feedback, automated welding, and teleoperation of vehicles and handling equipment. Ultimate applications include agriculture, the automotive industry, hostile environments, and the NASA Space Station. Major accomplishments to date include:

- seam-tracking systems for arc welding robots
- artificial vision system based on laser triangulation techniques
- a series of modular automated work-performing components
- automated inspection using a vision system, tactile sensors, and robot
- a laser-scanning 3-D range camera
- real-time multiprocessor operating systems and real-time control links
- active modal control of flexible manipulators in space applications
- a robot capable of lifting thousands of pounds with a rotating axis allowing five degrees of freedom
- remote repair tooling for hostile environments

The status of research and development activity, as it pertains to specific areas of robotics, is outlined in the text which follows.

Robotics Control

Facilities investigating robotics control include: CRS Plus (machine control and instrumentation directed towards development of small robots), NRC's Division of Electrical Engineering (NRC/DEE) (knowledge-based task planning and collision avoidance), the Division of Mechanical Engineering (NRC/DME) (kinematics and dynamics, supervisory control, and intelligent control), the National Aeronautical Establishment (robotics control systems), Robotics Systems International (RSI) (robotic control architectures for teleoperator systems involving voice-controlled robotics, servo-control of high-powered robotics systems, manipulator geometries and kinematics), Servo-Robot (adaptive control of the welding process), Spar (resolved motion control, active compliance, trajectory planning, heuristic control, flexible structure control, development of robot control languages), and Vadeko (hierarchical, adaptive controls).

Man-Machine Interface

Many organizations such as Spar Aerospace are focusing on aspects of man-machine interface in their robotics research. This includes: remote manipulation, off-line programming, graphic simulation, and so on.

Horizon is doing research on real-time application simulations. The Electrical Engineering Division of NRC studies computer graphics and man-machine interaction, while the DME does research and development on man/machine supervisory systems and off-line programming of industrial robots.

RSI's research and development effort includes the ergonomics of the man-machine interface and supervisory control of man-in-the-loop robotics systems, while Vadeko is developing off-line programming and graphic simulation.

Sensors and Vision Systems

Canadian researchers are making significant advances in the field of sensor development crucial to the development of adaptive robotics systems. Sites within this group include: Diffracto (machine vision as a method of robot guidance and optical inspection of surface defects and dimensions), NRC's DEE and NAE (optoelectronics, computer vision and pattern recognition for robot control), NRC/DME (intelligent control of sensor/robot systems), the Centre de Recherche Industrielle de Quebec (CRIQ) (machine vision and pattern recognition for general automation projects including robotics sensors), RSI ("telepresence" through improved sensing technology to provide vision and feedback on position, force and torque), Servo-Robot (developed an artificial vision system based on laser triangulation), Spar (vision feedback technology for use in teleoperator or robotic control systems), and Xenotech (developed an intelligent vision system based on the binary system yielding four levels of grey).

Manipulator, Gripper and Wrist Design

Among the companies developing robot arm technology are Horizon and Vadeko, both of which design and develop end-of-arm tooling. Horizon develops remote manipulation techniques, and gripper and wrist designs, while Vadeko develops end-of-arm tooling and specialized grippers as marketable products.

NRC's National Aeronautical Establishment works on the Canadarm, while NRC/DME studies the supervisory control of remote programmable manipulators. Also, Spar has an entire branch devoted to remote manipulator systems, with the ultimate aim of integrating manipulator control, AI and machine vision.

Robot Design

Clay-Mill has developed a robot with five degrees of freedom and heavy lifting capability while the objective of CRS Plus is to develop small sophisticated robot systems.

Locomotion

RSI develops and produces remote manipulator technology and control for subsea vehicles.

Artificial Intelligence Applied to Robot

The application of artificial intelligence to robotic systems is one of NRC/DEE's specialty areas. For Spar, it involves the development of task knowledge representation as well as the use of AI and machine vision for manipulator control.

Systems Architecture

Research into systems architecture is performed within NRC/DEE (multiprocessor system architectures for real-time computing, with a focus on parallel computing architectures and software engineering), RSI (high level

on-line and off-line robot programming languages), and Vadeko (real-time control software and operating system software).

Applications Development

The applications to which robotics research and development in Canada is ultimately directed, involve the whole range of industry and work environments. Horizons, for example, has agricultural applications as its goal, while Spar looks to future business both in space and terrestrial applications for its technology. Some of the main categories of robotics applications are discussed below.

Automotive

Clay-Mill designs and builds specialized automotive tooling and robotic systems for heavy duty applications. The Ontario Robotics Centre (ORC) has developed the conceptual solution for automated inspection of an automotive instrument panel using a vision system, tactile sensors, and a robot.

Manufacturing

Sites at which the application of robotics to manufacturing is being investigated or implemented include: Bata (developed a programmable materials cutting table with a water knife, and a 3-D CAD system for shoe design), Horizon (automatic factory concepts), Vadeko (CAD/CAM integration into its factory automation development), Promatic (developed a series of modular, interrelated, automated work-performing components), NRC/DEE (complex sensory-based tasks in a partially unstructured environment such as flexible assembly), ARC and CRIQ (implementation of robotics technology in the industries of their respective provinces), and the ORC (integrates off-the-shelf robotics into existing manufacturing processes).

Mining

CANMET performs research and development which addresses the short-term needs of industry for automating segments of the mining operation. The centre also has a major program underway to develop a comprehensive automated underground hard-rock mining system. Companies like INCO, Spar and Vadeko look to mining in investigating applications for their technology.

Space

Spar developed the Canadarm for NASA's Space Shuttle and is developing a servicing system for the NASA Space Station.

Subsea

One of RSI's major markets is subsea vehicle manufacturers.

Welding

Welding is a highly specialized application of robotics technology.

Among the Canadian organizations achieving major developments in welding robotics are Servo-Robot and the Welding Institute of Canada (WIC). Servo-Robot conducts research and development to develop robotic welding systems using seam tracking and adaptive real-time control. Their objective is to develop an integrated vision system, intelligent controller and programming system for various types of welding. The WIC performs research into the adaptive control of welding parameters through weld-pool monitoring and infrared vision at NRC laboratories.

Education

Because robotics is a new technology rapidly entering the workplace, education of those who need to understand it is an important part of the total process of automating Canadian industry. In this end, several companies provide robotics training facilities. Among these are Horizon (robotics education through seminars using training robots), the Ontario Robotics Centre (seminars in-house using its industrial robot collection as teaching aids), CRS Plus (prototype teaching robot), and RSI (produces small robots as educational tools).

Hostile Environments and Hazardous Waste

The applications of robotics technology to hostile environments eliminates danger to human workers and in many cases permits work to be done which simply could not be done by other means. CRNL's research and development efforts in this regard are to implement robotics technology in the nuclear environment. CRNL also foresees the transfer of their own robotics technology to non-nuclear sectors. Vadeko's activities address development of a remote repair system for nuclear reactor maintenance. RSI develops rugged, compact electronic packaging for hostile environments including hazardous waste handling, and telemanipulator systems and tools for remote and hazardous environments.

3. THE RESEARCH & DEVELOPMENT EFFORT OF CANADIAN POST-SECONDARY EDUCATIONAL INSTITUTES

In this chapter, university (and college) sites at which robotics-related activities are presently taking place are profiled. Due to differences in levels of research effort, as indicated in the questionnaire responses, three types of entry formats were produced. For sites which indicated a small research effort, a minimal number of publications and/or a research team which consists of only a few individuals, the entry was produced as an overall summary of the site. On the other hand, sites at which a high level of robotics-related research is being performed and which therefore have a large research team and a great number of publications to their credit, were entered using a detailed format which addresses individual areas of the site and its research. The third entry format was used for the colleges and presents only robotics facilities and the personnal associated with robotics.

For purposes of ease of use and fairness (i.e., not ranking research effort) entries within the chapter are arranged geographically by province (West to East) and alphabetically within a province.

3.1 Research and Development Centres

The sites presented in this section account for two groups performing robotics research. The first group of sites consists of those at which research which is directly related to robotics, at this time, is being undertaken. This research addresses such areas as manipulation, control, locomotion, communication, sensors, actuators, materials and applcations. The second group of sites consists of those at which research applicable to robotics is being undertaken. This research may involve disciplines from computer science, psychology or physiology and addresses such areas as computer vision (and biological vision as it relates to computer vision), artificial intelligence, and computer aided analysis. Site entries from each of the two groups are intermixed according to geographical and alphabetical ordering.

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I) Site Data

Robotics research and development started at UBCME in July 1982 with the arrival of Professor D.B. Cherchas and F. Sassani and has since grown to include a research, graduate, and limited undergraduate teaching program. Research is both grant funded (NSERC Operating Grants $25,000/yr) and contract funded ($75,000/yr)

Research facilities include: a PUMA 560 robot (VAL II), a VAX 11/750 computer, a Silicon Graphics IRIS 1400 graphics terminal (32 bit host computer, Ethernet link to VAX), an NC lathe, 2 NC machines and a number of graphics terminals and plotters. Expansion plans include procurement of updated NC machines and a vision system.

II) Personnel Data

Principal Researchers:

Prof. D.B. Cherchas	Associate Professor	controls, dynamics
Prof. F. Sassani	Assistant Professor	flexible manufacturing

In addition, 7 graduate students (1 Ph.D., 6 M.A.Sc.) are supervised.

III) Research Activities

The main areas of research are automatic control theory for end point control, robot mobility, automatic programming of robots, and NC machine cell programming. The main objective of the research is the addition of sensing capabilities and intelligence to robotic devices.

The group is specialized in control theory, dynamics and automatic programming. Development of a technique for automatic programming of welding robots, welding robot sonar range data processing, guidance software for a mobile robot, and development of closed loop and point algorithms are considered to be the major accomplishments of the group to date. The long term goal is to use the results of AI researchers to improve robot control at a high level.

Research software consists of an "Expert Welder" module for automatic programming of welding robots which was developed, VAL II software for the

PUMA 560 which was purchased and a "MOVIE BYE" motion simulation package for use on the IMS 1400 terminal, also purchased.

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BRITISH COLUMBIA, UNIVERSITY OF

Department of Electrical Engineering

Joint Robotics and Teleoperator Laboratories

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Professor P.D. Lawrence
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I) Site Data

Activities related to robotics and teleoperation were initiated in 1983 within the Department of Electrical Engineering. The research group is affiliated with the Department of Mechanical Engineering via the Joint Robotics and Teleoperator Laboratories.

Facilities available for research include: a Robotic Systems International RT3 6 DOF DC servo robot, an Imaging Technology IP-512 system, a Floating Point Systems FPS 100E Array Processor and a VAX 11/750, a PDP 11/23, an HP 9000 and an IBM-PC computers.

Funding for the research and equipment is provided by NSERC Operating Grants, the British Columbia Science Council and Robotic Systems International.

II) Personnel Data

Principal Researcher:

Prof. P.D. Lawrence	Associate Professor	computer applications in remote manipulators and signal processing

Additional Researchers:

Prof. E. Bohn	Professor	control systems
Prof. M. Davies	Associate Professor	control systems
Prof. G. Dumont	Adjunct Professor	control systems
Prof. W. Dunford	Assistant Professor	power control
Prof. J. McEwen	Adjunct Professor	Biomedical Engineering
Prof. D. Pulfrey	Professor	LSI design

Prof. R. Ward	Assistant Professor	image processing, control systems

III) Research Activities

Research areas include: human interfaces for teleoperation, image analysis and compression, and adaptive control and learning systems. The group's research objectives are to improve human control in industrial manipulation systems and to design adaptive systems for manipulator control. Major developments to date include: contributions to the theory of the reconstruction of non-uniformly sampled images, development of methods (and software) for digital processing of stereo images, quantitative evaluation of human factors in subsea manipulation using speed recognition and automated TV camera controls, and the design of an integrated circuit for kinematic conversions for robotic control (fabrication in progress).

Close communication is maintained with the Departments of Mechanical Engineering and Computer Science, Robotic Systems International (Sidney, B.C.), International Submarine Engineering, MacMillan Bloedel Ltd. and Andronic Ltd.

IV) Bibliography

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BRITISH COLUMBIA, UNIVERSITY OF

Department of Computer Science

The Laboratory for Computational Vision

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Prof. R.J. Woodham
(604) 228-3061

I) Site Data

History and growth:

The Laboratory, established in 1974, is a research group in Computer Science at UBC. Alan Mackworth was appointed in 1974, having just completed his doctoral research under Max Clowes at the University of Sussex. From the outset, research focused on two application domains: interpreting Landsat satellite imagery and interpreting hand-drawn sketch maps. In these domains, the problem of representing and using cartographic and geographic knowledge became central. Mackworth and his students pioneered applications of the computational vision paradigm to remote sensing.

In Canada and particularly in British Columbia, there is a strong need for trained workers in remote sensing. Accordingly, to strengthen the area at UBC, P.A. Murtha (Forestry and Soil Science), Mackworth, A.L. Farley (Geography) and H.R. Bell (Civil Engineering.) jointly proposed an Interdisciplinary Graduate Program in Remote Sensing which was funded by the Universities Council of British Columbia (UCBC) through the UBC Board of Governors as a Program of Excellence in 1977. Under this program three people were hired: Bob Woodham on a joint appointment between the Faculty of Forestry and the Department of Computer Science, with responsibility for the development of the remote sensing program, and two technical support people (one in Murtha's laboratory in Forestry and one in the Laboratory for Computational Vision). These three positions are funded on a continuing basis.

Woodham joined the laboratory in 1978, having spent one year as a Research Scientist in the MIT Artificial Intelligence Laboratory after completing his doctoral research there under Berthold Horn in 1977. At UBC, Woodham has continued to develop a computational vision approach to remote sensing. In particular, Woodham has pioneered the application of digital terrain models (DTM's) in Landsat image analysis.

It was soon evident that the research groups involved required a substantial extension to the digital image analysis computational facility in order

to carry out their research programs. Accordingly, Mackworth and Woodham, together with Murtha, W.J. Emery (Oceanography), J.R. Auman, G.G. Fahlman, P. Hickson, T.K. Menon and G.A.H. Walker (Geophysics & Astronomy) and J.L. Paul and W.M. Thurlbeck (Pathology), applied for an NSERC Major Installation grant entitled, "Digital Image Analysis System Expension". The application was partially funded by NSERC in 1981. Additional funds were supplied by UBC and by MRC.

Bill Havens joined the Laboratory in 1981. Havens completed his doctoral research under Mackworth in 1978 on knowledge representation for computational vision. He spent the intervening three years first at Simon Fraser University and then at the University of Wisconsin at Madison where he established a computational vision laboratory.

Mackworth was named Director of the Laboratory in 1981. The Director is responsible for overall policy, administration and funding in consultation with members of the Management Committee, and with the support of the other faculty members in the Laboratory. The Management Committee consists of Emery, Fahlman, Havens, J. Leigh (Computing Centre), Mackworth and Woodham.

Woodham was named Director of the Laboratory in November 1984 when Mackworth became coordinator of the UBC node in the Artificial Intelligence and Robotics program of the Canadian Insitute for Advanced Research (CIAR). Both Mackworth and Woodham were appointed Fellows of the CIAR in July 1984.

Facilities:

The Laboratory for Computational Vision maintains a Digital Image Analysis System. The original Program of Excellence grant provided funds for the acquisition of a digital image processing and display system, a Comtal Vision One that was installed in 1978. The UBC Computing Centre was asked to provide a high-speed link for the transmission of image data between their system, an Amdahl 470 running MTS, and the Comtal. The hardware cost of that link was approved as part of their budget. The high-speed link was installed in the summer of 1980.

Major system extension occurred in 1981. The main computer supported now is a DEC Vax 11/780 with various peripherals. The system also included a high resolution Optronics C-4500 colour film scanner/writer, two image display workstations, the Comtal Vision One and a Raster Technologies Model One/25, and an assortment of other hardware for image input, output and communications.

The system provides hardware and Unix based software for image input, processing and output on video and a variety of film products. A software library for image manipulation, radiometric and geometric correction, registration, filtering, classification, enhancement and interpretation is available using a standard image representation. Some of this software library is also supported by the Laboratory on the Computing Centre's Amdahl/MTS system. A variety of software tools for artificial intelligence and computational vision research, such as knowledge representation languages, has been developed and supported on the Vax/Unix system.

Affiliations:

Primary affiliations are with: 1) the UBC Department of Computer Science; 2) the UBC Interdisciplinary Graduate Program in Remote Sensing, Faculty of Forestry; and 3) the UBC node in the Artificial Intelligence and Robotics program of the Canadian Institute for Advanced Research.

Source(s) and amounts of funding:

The operating budget of the Laboratory for fiscal year 84/85 is $160,695 made up as follows:

Source	Amount
NSERC	110233
University	33642
CIAR	16312
Other	508

Additional funding for research supported by the Laboratory is provided by the individual operating grants of the Faculty members involved.

Fee structure for external services:

The Comtal Vision One image display is freely available and heavily used by researchers from many UBC departments. The Vax 11/780 system is used mainly by the research groups of the eleven investigators on the NSERC Major Installation Grant. Due to the delicate nature of the Optronics, all film scanning and writing requests are handled by Nedenia Krajci, the Remote Sensing technician. Outside users are billed for film scanning and writing at an hourly rate to recover the cost of technician's time.

Clientele:

The facility is primarily available to UBC researchers. Work in computational vision, forestry, oceanography, astronomy, geography, physics, electrical engineering, soil science and urban planning has been carried out.

The film scanning and writing capability of the Optronics is unique and has been made widely available to UBC researchers and to researchers from other universities and from private industry.

External users are screened based on the extent to which the facility contains unique resources essential to their research, the extent to which they can contribute expertise to the facility in, for example, computer networking or programming language development, and the extent to which their research relates to the research activities of the Laboratory for Computational Vision.

Plans for expansion:

The Laboratory is continuing to restructure its computing equipment into a distributed environment on a local area network. This is to improve the access to, and productivity of, their existing facilities. It is also to prepare for the addition of new facilities. A SUN Model 120/FS is on order to

be an ethernet server for the Raster Technologies Model One/25. This ethernet is shared with other machines and resources in the UBC Department of Computer Science.

Increasingly, the Lab's research requires the integration of the computations of early vision, principally numeric in form, with those of later vision, principally symbolic in form. The experimental component of the research program is outgrowing current resources. The majority of software development now occurs either directly in Lisp or indirectly in knowledge representation systems embedded in Lisp. There now exist several commercial suppliers of Lisp machines that are software and hardware compatible with the current environment. Grant applications to fund Lisp machines for the Laboratory are to be prepared in 1985/86.

II) Personnel Data

Director:	R.J. Woodham	Forestry/Computer Science
Faculty:	W.S. Havens	Computer Science
	A.K. Mackworth	Computer Science
	R.J. Woodham	Forestry/Computer Science
Affiliated Faculty:	W.J. Emery	Oceanography
	G.G. Fahlman	Geophysics & Astronomy
	J.E. Hay	Geography
	P.A. Murtha	Forestry
Guest Faculty:	R. Reiter	Computer Science
Staff:	T. Lee	CIAR Programmer/Analyst
	N. Krajci	Remote Sensing Technician (part time)
	F. Pronk	Laboratory Manager
	M. Vink	CIAR Secretary
	C. Whitehead	Admin. Assistant (part time)
Affiliated Staff:	P. Boyle	Computer Science
	P. Chan	Computer Science
	J. Demco	Computer Science
	D. Laplante	Oceanography
	P. Nowlan	Oceanography
	R. Sample	Computer Science

Graduate Students:

At the present time, 13 graduate students (4 Ph.D., 9 M.Sc.) and 9 affiliated graduate students are associated with the laboratory.

III) Research Activities

The UBC Laboratory for Computational Vision focuses on applications of computational vision to remote sensing and geographic information systems. Within the list of areas given in Appendix A of the questionnaire, areas of specialization include: knowledge representation; world modeling; and pattern recognition. Although the application domain is primarily remote sensing, application areas of specialization also include: inspection and maintenance; space environments; and agricultural environments.

The objective of the Laboratory for Computational Vision is to make machines see, partly to make them more useful and partly to learn more about the nature of perception itself. The usefulness of machines that see is clear. Laboratory staff feel that it is also clear that the ideas of computational vision are the principle scientific path towards making machines see. Moreover, it is believed that computational vision is providing a new language for algorithmic theories of perception.

The research areas of the principal faculty and their students are summarized as follows:

Knowledge Representations and Algorithms for Computational Vision (A.K. Mackworth)

In the cooperative interpretation project, Mackworth and Mokhtarian have discovered a new representation for knowledge of shape and an algorithm for computing and using it. This representation has successfully been used to match Landsat imagery to a stored map data base. Further experiments with Mapsee2 were carried out with Havens and Mulder. A new hierarchical arc consistency algorithm was invented, and its theoretical and practical limits explored. Further results on investigation of consistency algorithms for constraint satisfaction problems have been reported.

Archibald carried out a collaborative project between the Laboratory and Nestor Burtnyk's laboratory at NRC using Marc Rioux's laser range finding 3D camera for robotics. Jan Mulder has finished the research for his Ph.D., implementing Mapsee3, and is now completing his thesis.

Further work is ongoing with Katz on perspective stereo and the structure of scale space. Investigations of the logic of depiction, cooperative interpretation, conformal mappings and the domain theory of vision with applications in remote sensing and cartography form the focus of current and future work.

Photometric Methods for Image Analysis (R.J. Woodham)

The objective of the research is to identify constraints and to define computations that make vision possible. Specific progress has been made in: the geometric and radiometric correction of multispectral scanner data; representations for shape, orientation and attitude; and the exact reproduction of digital colour images.

A high throughput system for the geometric correction of satellite imagery, including relief displacement correction, has been demonstrated in the Ph.D. thesis of Wong. This work was done in collaboration with MacDonald, Dettwiler and Associates, Ltd. Radiometric correction deals with elevation, slope and aspect dependent effects. A model has been developed with Lee to account for different amounts of solar irradiance, sky irradiance and path radiance across a scene. The model has been successfully applied to Landsat MSS images of a test site near St. Mary Lake, B.C.

Objects can be represented by specifying area as a function of surface orientation, forming the Extended Gaussian Image (EGI). Little's Ph.D. thesis exploits the EGI. An earlier algorithm to invert the EGI of a convex object introduced a novel geometric construction called the "mixed volume". Using raw surface data obtained from photometric stereo, a comparison of partial EGI's, using mixed volume as a similarity measure, determines the attitude of a known object from a sensed portion of its surface. This allows a robot to pick mixed parts out of a bin.

Heiss's M.Sc. thesis implements a software system to numerically calibrate the Optronics C-4500 film writer. The triplet of digital exposure values required to produce a desired triplet of integral dye layer densities for an arbitrary combination of film type and processing can be determined. This is a necessary prerequisite for ongoing work on the exact reproduction and enhancement of digital colour images.

New research is underway using regularization theory to unify earlier methods for determining shape from shading. The perception of self-similar textures is being pursued with Rensink and in collaboration with A. Treisman in Psychology. Semantic constraints between vector and raster representations in remote sensing and geographic information systems is being explored with Majka. Two Forestry graduate students, Gray and Dumoulin, are independently applying earlier quantitative techniques to practical problems in forestry remote sensing.

Representational Adequacy for Visual Knowledge (W.S. Havens)

Visual perception tasks are being explored as an experimental vehicle for understanding knowledge representation. What forms of knowledge underly the process of vision and how can that knowledge be represented and applied in a computer program? The basic assumption behind this work is that there exist natural organizational principles to all recognition tasks and by studying such tasks this structure can be elucidated. In particular, composition and specialization appear to be two major aspects of recognition processes. To understand these processes, a formal model of consistency for schema-based knowledge representations has been developed.

Schema knowledge representations have been used to understand imagery. The design of Very Large Scale Integrated (VLSI) circuits remains an art that has not kept pace with the VLSI hardware technology. Very expensive errors proliferate into fabrication despite powerful design rule checkers and circuit

simulators. Havens and Alon have demonstrated an alternative approach that recognizes an abstract logic function description of the VLSI circuit from its mask artwork. The technique reverses the design process thereby recovering the logical function actually fabricated in the chip.

Major accomplishments/developments to date:

Mackworth's early work introduced the use of metric, rather than topologic, constraints in the interpretation of line drawings of polyhedral scenes. He advocated the gradient space representation for surface orientation. Gradient space remains one of the basic tools of current research in computational vision.

Many computational vision tasks, as well as others, can best be expressed as constraint satisfaction problems. These problems had typically been solved by backtracking or by poorly understood "filtering" algorithms. Mackworth described a class of algorithms, known as network consistence algorithms, which provide both a unified framework for anlaysis and practical techniques to eliminate local inconsistencies in networks of relations.

Woodham's work formally extended Horn's approach to shape from shading. Woodham also introduced the technique of photometric stereo which has become the first practical realization of methods to determine object shape based on a photometric approach to computational vision.

Woodham has applied his techniques, originally developed for automatic inspection of surface defects in metal castings, to problems in remote sensing. In particular, Woodham has pioneered the use of digital terrain models (DTM's) for the geometric and radiometric correction of satellite image data.

Havens developed the knowledge representation language MAYA, a multiprocessing dialect of Lisp that provides data structures to represent schemata and control structures to combine top-down and bottom-up approaches to recognition. Havens has contributed substantially to the Laboratory by supervising high-level language development for its research and by designing, implementing and supporting a library of image representation and access procedures.

The Laboratory for Computational Vision has developed a digital image analysis facility that provides hardware and software for image input, processing and output on video and a variety of film products. A software library for image manipulation, radiometric and geometric correction, registration, filtering, classification, enhancement and interpretation is supported on Unix 4.2BSD using a standard image representation. Versions of this software have been provided to several sites including: MIT, the University of Western Ontario, Queens University and Simon Fraser University.

Major software programs either developed or used:

mapsee	- program to interpret hand-drawn sketch maps
MAYA	- a knowledge representation language embedded in Lisp
Multilisp	- the Interlisp virtual machine in Pascal

A standard image file and graphics file format with interfaces to C and Franzlisp and support for the Comtal Vision One, the Raster Technologies One/25, Telidon, the Optronics C-4500, the Apple MacIntosh, magnetic tape and the Imagen laser printer.

Parties with whom the Lab communicates:

The two CIAR Fellows in the Laboratory, Woodham and Mackworth, communicate with the other CIAR Fellows at UBC, Reiter, Treisman and D. Kahneman, as well as with other CIAR Fellows at McGill and Toronto.

The Laboratory is associated with the UBC Interdisciplinary Graduate Program in remote Sensing and cooperates with members of the UBC Remote Sensing Council.

The Laboratory collaborates in its remote sensing research with MacDonald, Dettwiler and Associates, Ltd., with the Canada Centre for Remote Sensing and with the B.C. Ministry of Forests.

The Laboratory collaborates in its robotics research with laboratories in NRC and MIT. The Laboratory also cooperates with two robotics groups at UBC, D. Cherchas et al. in Civil Engineering and P. Lawrence et al. in Electrical Engineering.

Position in robotics R&D community:

As an academic teaching and research Laboratory, the Laboratory's principal role in the Canadian research community is to provide a research environment for the development and testing of advanced ideas in artificial intelligence, knowledge representation, world modeling, computational vision and graphics. It trains the students who become robotics researchers in Canadian universities, government agencies and industry.

Particular expertise is in remote sensing and geographic information systems. This is an area of immense practical importance to Canada. Our resource-based economy and vast, often inaccessible, land and water bodies make remote sensing the only viable technology for resource management. Canadian government and industry play a world leadership role in developing and supplying this technology. At the UBC Laboratory for Computational Vision, a focus of excellence for research and education in the field has been established.

Participation in the Joint Coordinating Forum on International Cooperation in Advanced Robotics:

The Laboratory for Computational Vision provides a research environment for the development and testing of advanced techniques in machine vision. Intelligent vision systems will be a critical component of many advanced robotics projects. Thus, it is logical that robotics projects arising from the Forum could benefit from the participation of the Laboratory. By the same token, there are projects that individuals in the Laboratory would enthusiastically pursue.

As described above, collaboration already occurs between the Laboratory and government (NRC, CCRS, BC MOF) and industry (MDA). New projects of interest to members of the Laboratory are being considered. Woodham is involved, along with other CIAR Fellows, academics and researchers from SPAR Aerospace, in planning for Canada's involvement in the U.S. Space Station. Woodham is also a member of the Image Analysis Systems and Artificial Intelligence Working Group (IASAIWG) of the Canadian Advisory Committee on Remote Sensing. This working group includes representatives from university, government and industry and is concerned with the development, in Canada, of remote sensing and geographic information systems.

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SIMON FRASER UNIVERSITY

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I) Summary

Robotics research is in the early stages of development within SFU's Faculty of Engineering Science which was just recently established itself (established March 1984 and scheduled to become a school within the new Faculty of Applied Science in 1985). Research facilities include an "Excalibur" manipulator prototype (Robotic Systems International - Sidney, B.C.) and access to IBM-PC's, a VAX and an IBM mainframe. Funding for robotics research and equipment in the amount of $45,000 for 1984/85 was provided by SFU.

Robotics-related research is preformed primarily by Professor McGeer (control systems) whose research interests include: manipulator control, collision avoidance, pneumatic manipulator control and autonomous vehicle design including acoustic navigation and vision-based guidance. The major development to date has been the production at an acoustic navigation system for a mobile robot.

The research group maintains communication with Robotic Systems Int'l. (Sidney, B.C.), MacDonald, Dettwiller, and Associates (Richmond, B.C.), Medical Engineering Research Group (Vancouver General Hospital) and with UBC's Electrical Engineering Department.

II) Bibliography

None at this time.

SIMON FRASER UNIVERSITY

Department of Computer Science

Burnaby, British Columbia
V5A 1S6

Professor B.V. Funt
(604) 291-4277

I) Summary

The Department of Computing Science at Simon Fraser University includes one researcher, B.V. Funt, who has a primary interest in Computer Vision. There are however, several other faculty members in Artificial Intelligence: N. Cercone, V. Dahl, R. Hadley, and J. Delgrande. In terms of the overall AI effort, the group is young but has great future potential.

The facilities include two VAX 750's, numerous SUN workstations, an International Imaging Systems Model 75 image processing system and two IRIS graphics workstations. Funding sources include NSERC and the Science Council of British Columbia.

The computer vision effort involves Funt and two graduate students. A primary application area is that of the analysis of CT-scans of sawlogs in order to identify defects in logs that would affect lumber quality. A computer program has been successfully implemented that identifies knots, rot, holes and areas of good wood from these images on the basis of region density, texture and shape. A second project deals with computer colour perception in three-dimensional scenes, while a third project is underway on the study of image specularities.

II) Bibliography

1. Bryant, E., and Funt, B., Feature constraints for computer interpretation of CAT-scan images of logs, Proceedings of the Fourth Biennial Conference of the Canadian Society for Computation Studies of Intelligence, Saskatoon, May 1982.

2. Funt, B., Bryant, E., A computer vision system that analyses CT-scans of sawlogs, IEEE Proceedings of Conference on Computer Vision and Pattern Recognition, San Francisco, June 9-13, 1985.

3. Funt, B., Bryant, E., Toward automatic sawlog defect detection using computer tomography, Proceedings of Forintek Canada's Technical Seminar: Scanning Technology for the Eighties, Vancouver, Nov. 15-16, 1984.

ALBERTA, UNIVERSITY OF

Department of Mechanical Engineering

Edmonton, Alberta
T6G 2E5

Professor R.W. Toogood
(403) 432-4712

I) Summary

Robotics research activity has been ongoing within the department since 1982. The principal researcher is Professor Toogood who supervises three graduate students in robotics research. Facilities, which are primarily for use in the undergraduate robotics course, consist of two Mitsubishi Movemaster robots with IBM-PC controllers and access to the university's mainframe (Amdahl 5860) computer. The robots are used as test-beds for developed high-level languages while dynamic modelling is performed on the mainframe. The students' research addresses effects of joint misalignments on the accuracy of tool velocity and positioning, and robot grippers for aiding the disabled.

II) Bibliography

None at this time.

ALBERTA, UNIVERSITY OF

Department of Psychology

Image Processing Laboratory

P220 Biological Sciences Building
Edmonton, Alberta
T6G 2E9

Professor T.M. Caelli
(403) 432 5330

I) Summary

Robotics-related research is performed in the Image Processing/Robotics Lab by Professor T.M. Caelli. The lab was established by Professor Caelli in 1983 with NSERC funds and now possesses the following research facilities: an RB robot to which has been added an arm, speech and ultrasound, an ITI Image Processing System with peripherals, and three PDP-11/23 computers.

The lab is affiliated with the Departments of Electrical Engineering and Computer Science. Funding from NSERC amounted to $63,000 in 1983, $33,000 in 1984, and $33,000 in 1985.

Professor Caelli is joined in his research efforts by four graduate students and is expecting two post-doctorate researchers next year. The principal research areas include: eye-hand coordination in object handling, development of coding techniques for the detection of images under transformations, and pattern recognition in a dynamic context. The group applies their experience with human and computer vision to robotic vision.

II) Bibliography

Professor Caelli has (co)authored some 77 publications. However, since the subject matter of these papers deals primarily with biological vision, they are not presented in this guide.

CALGARY, UNIVERSITY OF

Department of Computer Science

2500 University Drive, N.W.
Calgary, Alberta
T2N 1N4

Professor J.R. Parker
(403) 284-6015

I) Site Data

Robotics-related research activities have been carried on in the Department of Computer Science for approximately three years. Facilities available for such research include: a Rhino XR-2 robot, a video digitizer, a PDP-11/44 computer and access to two VAX 11/780's and a CDC Cyber 205 supercomputer. Funding for research and equipment is through grants, primarily NSERC, as no revenue-generating services are provided.

The principal researcher is Professor J.R. Parker whose interests lie in computer vision and its application to robotics. In addition, research is conducted by three research assistants (W. Lee - image analysis, D. Stephen - robot control, D. Grant - operating systems) and one graduate student.

Research areas include vision for robot control and computer simulation of robot systems (XR-2 simulation on VAX with video output). For real-time control of a robot from vision-based input, the laboratories Wicat controller obtains input from a video digitizer, or simulated input, via the VAX and uses this to control the XR-2.

Major developments to date include: development of an integrated simulation/robot control system which provides graphics output, and development of a gradient-based feature-extraction method. Software produced in the course of these developments includes: a program to generate 3-D graphics screen output, a computer animation program, and a robot simulation/control program.

II) Bibliography

The majority of the literature which has been produced deals with simulation and software design. A sampling of robotics-related publications is presented below.

1. Parker, J., Simulating a robot arm using graphics and animation, Conference on AI, Graphics and Simulation, San Diego January, 1985.

2. Parker, J., Lee, W., and Stephen, D., A Simple Robot Arm Control Method, October 1984.

3. Parker, J., Gradient Following for Feature Extraction in Character images, (in press).

4. Parker, J., Grant, D., Experiment with a Vision-Driven Compiler, (in press).

SASKATCHEWAN, UNIVERSITY OF

Department of Electrical Engineering

Saskatoon, Saskatchewan
S7N 0W0

Professor H.C. Wood
(306) 966-5379

I) Site Data

Robotics research is conducted in the Electrical Engineering, Computational Science and Mechanical Engineering Departments. In addition, research is conducted in the Control Engineering and Biomedical Engineering Divisions of the College of Engineering.

The following facilities are available for research on robotics: two VAX 11/780 and one DEC 1160 computers, various microcomputers, a CNC lathe, a teaching arm, an in-house developed mobile robot, and a vision system. Funding has been obtained from Northern Telecom which provided $6,000 for the purchase of the vision system and an application has been submitted to the Saskatchewan Ministry of Science and Technology for a grant of $125,000.

II) Personnel Data

Principal Researchers:

Prof. R. Burton	-	hydraulic actuators, servo control
Prof. M. Gupta	-	control systems (particularly "fuzzy" controllers)
Prof. K. Takaya	-	man/machine interface, biomedical myoelectrics
Prof. J. Wilson	-	agricultural/mining automation
Prof. M. Wood	-	electronic and computer control, sensors, vision

III) Research Activities

The research areas include hydraulic and electric control systems, simulation, sensor development, vision, and application-oriented research in the areas of agricultural and mining activities. Uranium and potash mining and processing are especially targets of investigations aimed at eliminating potential hazards to human operators and to increase productivity.

The College of Engineering has an agreement with Horizon Robotics of Saskatoon to cooperate on research and development projects, especially in the area of mining activities. The researchers also cooperate with the Saskatchewan Department of Science and Technology, the Saskatchewan Research Council, the Saskatchewan Department of Agriculture, and the University of Saskatchewan Department of Rehabilitiation Medicine.

Several graduate students are working in robotics-related projects. Some of the robotics-related research results have been published.

Work on hydraulic actuator position measurement and control, development of vision interface to computer, automation of some mining machines and agricultural equipment, and building of a mobile robot with two arms, sonar, voice remote control, and myoelectronic arms and hands are considered to be the major accomplishments of robotics research to date.

IV) Bibliography

None at this time.

MANITOBA, UNIVERSITY OF

Department of Mechanical/Industrial Engineering

Industrial Automation and Simulation Laboratory

Winnipeg, Manitoba
R3T 2N2

Professor O. Hawaleshka
(204) 474-9535

I) Site Data

The Industrial Automation and Simulation Laboratory is one of two laboratories (other is Manufacturing Integration Laboratory) in which robotics research is performed. It was established in September 1982 and its emphasis is on small-scale integrated production. The laboratory is affiliated with the Departments of Mechanical/Industrial Engineering, Electrical/Computer Engineering and with the Industrial Applications of Microelectronics Centre in Winnipeg. Expansion plans call for expanded laboratory facilities, co-operation with the Industrial Technology Centre (Manitoba) and co-operation with the South Winnipeg Vocational Institute in the areas of continuing education and industrial training.

Source(s) and amounts of funding:

University of Manitoba - operating	$260,000/yr.	
Province of Manitoba/University of Manitoba - capital	$238,000	1982/84
Province of Manitoba - ITC equipment	$ 65,000	1985
National Research Council - equipment	$125,000	1984
ASEA (Robots) Ltd. - equipment	$ 35,000	1984

II) Personnel Data

Principal Researchers:

Prof. S. Balakrishnan	Assistant Professor (Mechanical/Industrial Engineering)	manufacturing integration

Prof. W.L. Cleghorn	Assistant Professor (Mechanical Engineering)	dynamics, kinematics
Prof. A. De Groot	Assistant Professor (Mechanical/Industrial Engineering)	sensors, control
Prof. O. Hawaleshka	Associate Head (Mechanical/Industrial Engineering)	computer/graphic simulation, technology transfer
Prof. A. Kusiak	Associate Professor (Mechanical/Industrial Engineering)	optimization, control
Prof. S. Onyshko	Associate Professor (Electrical Engineering)	vision systems
Prof. E. Shwedyk	Associate Professor (Electrical Engineering)	information systems

In addition, the laboratory employs one full time technician and supervises eight graduate students (2 Ph.D., 6 M.A.Sc.).

III) Research Activities

The main orientation of research activities of the Industrial Engineering Group lies in the broad area of productivity improvement through manufacturing/production control, automation and associated appropriate technology transfer. Strong emphasis is given to applicability to small/medium industry with special relationships with the agricultural implement, apparel and furniture manufacturing as well as the physical distribution/warehousing industries. Applications of microcomputer/graphics are stressed throughout. Specific areas of research include:

1. Development of a computer-integrated manufacturing cell including manufacturing and robotic machinery, quality assurance and automated storage and retrieval systems. Process control (modelling and implementation of control models) using feedback sensors in typical FMS, development of high level part programming languages for CNC manufacturing, robot dynamics and control synthesis for manipulator arms.
2. Optimization of tactile sensors for robotic end effectors, integral with on-board VLSI processing of tactile data to permit direct

communication for robot control, reduction of computational loads and improvement of robotic operation speeds - all in the context of integrated manufacturing/production environments.

3. Production control software development for specific industrial environments including the development of appropriate databases.
4. Computer-graphics simulation of production/manufacturing processes in the metal machining as well as the garment manufacturing industries, including ASRS - Automated Storage and Retrieval Systems control software.
5. Computer-graphics simulation of the spread of dangerous substances under hostile environmental conditions for the development of decision-aids for emergency planning situations.
6. Computer-graphic simulator decision aids for transportation, scheduling and dispatching including optimal routing information subject to movement limitations with graphical mapping display.
7. Research into the problem of appropriate means of transfer of modern computer-integrated control technologies to targeted user industries.

Professor Hawaleshka's areas of interest include: computer graphic simulation of production systems, automated material handling, simulation of automated storage systems, simulation of flexible manufacturing systems and technology transfer. Professor Balakrishnan's interests include: automated manufacturing, adaptive control of robots, optimization of robot motion and flexible manufacturing cells. Professor De Groot is interested in sensor development and control of robots. Professor Cleghorn's interest is robot kinematics and dynamics, including manipulator joint trajectory optimization based on kinematic and dynamic constraints. Professor Onyshko's area is vision systems, robot control and co-ordination of robots with NC machines. Finally, Professor Shwedyk's interest is in the area of informaton systems.

The group co-operates with Manitoba's Industrial Technology Centre, agricultural implements manufacturers and apparel manufacturers.

Development of off-line control capability of industrial robots and production systems via microcomputers is considered the major research accomplishment of the Industrial Automation and Simulation Laboratory to date.

In the area of sofware, programs for off-line control of the ASEA and Teachmover robots, via an IBM-PC, have been developed.

IV) Bibliography

1. Hawaleshka, O., et al., Ten Years After: The experience with a robot (1972-1982), APICS Conference Proceedings, New Orleans, 1983.

2. Hawaleshka, O., Kumar V., Robotics in Industrial Engineering.

3. Hawaleshka, O., Development of a Small-Scale Flexible Manufacturing Cell.

4. Hawaleshka, O., Balakrishnan S., A. de Grott, et al., Microcomputers in a New Manufacturing-Control Oriented IE Program.

5. Hawaleshka, O., Balakrishnan S., Affordable Manufacturing Integration, 8th Production Automation Conference, Stuttgart. 1985.

6. Johnson, K., Simulation of continuous path motion using a point-to-point robot.

7. Podhoreski, R.P., Cleghorn W.L., Direct Joint Variable Solution of Redundant Manipulators, Tenth CAMCAM, 1985.

8. Wolfe, O.B., Robotics Laboratory Manual, University of Manitoba Industrial Engineering Laboratories, 1983.

CARLETON UNIVERSITY

Department of Mechanical/Aeronautical Engineering

Robotics and Control System Laboratory

Ottawa, Ontario
K1S 5B6

Professor J.Z. Sasiadek
(613) 231 2634

I) Site Data

The Robotics and Control System Laboratory, established in September 1983, incorporates the following research facilities: two Rhino robots with accessories, two Hyperion microcomputers, a programmable controller, a PDP-11, an EMCO NC machine and various hydraulic actuators. Expansion plans include the acquisition of a PUMA 560 robot computer with vision system.

Funding for the laboratory comes primarily from NSERC operating grants ($60,000 1984/87), however, contract research with Spar Aerospace and BNR also produces significant funds.

II) Personnel Data

Principal Researchers:

Prof. G. Kardos	Professor (Mechanical Engineering)	kinematics
Prof. J.Z. Sasiadek	Professor (Mechanical Engineering)	control systems, robotics

In addition, one full time laboratory technician and five graduate students are associated with the laboratory.

III) Research Activities

The researchers' principal objective is to develop sophisticated control systems for robots. To this end, their research areas include: adaptive control of flexible arms and stochastic control. In addition, pattern recognition is a primary research area.

Software developments consists of: ADA which was developed to control the position of a robot, and LATHE which was developed for use during the manufacture of various parts on the NC machine.

IV) Bibliography

1. Sasiadek, J.Z., Designing control systems for robots using expert systems, Proc. of 6th International Conference on Robotics and Automation, Santa Barbara, May 1985.

2. Sasiadek, J.Z., Designing kinematics and dynamics of robot using expert system, Proc. CAD/CAM and Robotics Conference, Toronto, June 1985.

CARLETON UNIVERSITY

School of Computer Science

Ottawa, Ontario
K1S 5B6

Professor J. Oommen
(613) 231-7545

I) Summary

The School of Computer Science at Carleton is a relatively new school (July 1979). It has a joint Master's program with the University of Ottawa and is currently proposing a PhD program. Facilities include a Honeywell mainframe, an INTEL system, a Lisp machine, a SUN, and various microprocessors. Funding is primarily from NSERC, at the $110,000 per year level. The School will expand and has been granted more faculty positions.

There are 12 faculty currently (F. Fiala is the School's Director). Of these twelve, 6 have interests in artificial intelligence, and of these, 2 have specific robotics interests. The six are: W.R. Lalonde, J. Nielson, J. Oommen, F. Oppacher, D. Thomans and J-R Sack. Oommen and Sack have robotics interests. In addition, two software engineers are employed by the school.

The principal research directions of these faculty members include: the design of fast algorithms for movability of objects in the presence of obstacles, the design of algorithms for hierarchies of movability problems, the design of object-oriented robot programming languages, and the design of stochastic algorithms for path finding.

The School's clientele includes INTEL, BNR and DY-4 Systems.

II) Bibliography

Papers produced by the School of Computer Science number some 66 publications. However, none of these relate to robotics or computer vision and so they are not presented in this guide.

CARLETON UNIVERSITY

Centre for Advanced Studies in Computer Aided Design
and Engineering (CASCADE)

Ottawa, Ontario
K1S 5B6

Professor J.A. Goldak
(613) 231-3627

I) Site Data

The Centre for Advanced Studies in Computer Aided Design and Engineering was formed in late 1982 as a result of an application led by John Goldak and Neal Holtz (Director - CASCADE) for an Ontario Government Board of Industrial Leadership and Development (BILD) grant to obtain engineering workstations. It was realized that there were significant research interests in common among the Departments of Mechanical and Aeronautical Engineering, Electronics, and Civil Engineering, and the Schools of Industrial Design and Business. CASCADE was formed to help manage the facilities purchased by the BILD grant, and to provide Carleton University with a focal point for research in the nationally vital area of Computer Integrated Design and Manufacturing. Specifically, CASCADE would act as a catalyst to bring together experts from all relevant disciplines on campus - to define common research goals, to organize research work, and to apply for funding.

The Centre for Advanced Studies in Computer Aided Design and Engineering (CASCADE) is dedicated to the advancement of Computer Integrated Design and Manufacturing (CIDM) through research and teaching, with a focus on three major areas.

- Civil and Mechanical Engineering - CAD/CAM and Building Sciences
- Electronics - VLSI and printed circuit board design and analysis
- Computer Science for CIDM - Data bases, man-machine interaction, software development tools

In these areas, CASCADE acquires, implements and evaluates world class CIDM software packages and develops in-house expertise in using them. Knitting these programs into integrated and easy-to-use software systems is the main task of researchers in CASCADE. While the CASCADE philosophy is to acquire software wherever possible, in selected critical areas, CASCADE develops software. For example, a nonlinear finite element analysis program is being developed because the available "black boxes" were considered inappropriate for research and teaching. In addition to CIDM application programs, CASCADE also aims to provide the best possible environment for software development including relational data bases, GKS graphics, and help, documentation and menu tools.

In short, the Centre provides an environment for the use and development of CIDM systems for real problems; it does this by helping to provide the essential ingredients of hardware, software and expertise.

Principal researchers consist of eleven professors, of various (non-robotic) specializations, and approximately 40 graduate students. The primary research areas addressed by this group are:

- Data bases for CIDM with consistency checks and integrity management
- Man-machine interaction: e.g. graphics, menus, help, etc.
- Development of applications programs in selected areas
- Use of applications software: e.g. PADL-2, IMP or SPICE

While no robotics-related research is performed by the Centre, its primary (potential) contribution to robotics is through its software packages. The ones which could be applied to robotics are:

PADL-2:

This solids modeller was implemented in July 1983 and is being integrated into the CIDM software system. A solid modeller has the capability to ensure that a component is 'real' in the sense that it could actually be made. Equally important it contains a structured data base for multi-component systems. Components are built by 'adding' or 'subtracting' primitive solids such as blocks, wedges, planes, cylinders, spheres, or toroids. Shaded colour scenes with hidden line removal can be displayed. The volume, weight, centre of gravity and moments of area can be computed. The solids model then serves as a preprocessor for finite element analysis. The models can be 'assembled' using attributes being developed by Rochester for tolerancing, surface finish, texture, and filets.

IMP:

IMP is a program for the dynamic or kinematic analysis of mechanisms such as linkages and machines. Included are kinematic constraints, prescribed motion, spring constants, damping factors and prescribed forces. The space arm was modelled using this approach. It is particularly useful for obtaining the loads on components needed for finite element analysis of stress and deflections in the components.

II) Bibliography

No robotics-related publications at this time.

McMASTER UNIVERSITY

Faculty of Engineering

Centre for Flexible Manufacturing Research
and Development

1280 Main St. W.
Hamilton, Ontario
L8S 4L7

Professor H.A. ElMaraghy
(416) 525-9140
Telex: 061-8347

I) Site Data

Robotics-related research at McMaster University is conducted in the Mechanical Engineering and Electrical Engineering Departments. Most experimental equipment supporting robotics research is located within the laboratories of the Mechanical Engineering Department. These facilities include: a Unimate 2000 robot, a Puma 600 robot, and a Seiko pick-and-place robot. (The Unimate 2000 robot is retrofitted with DC drives and control.) In addition to the three robots, the laboratory possesses: a retrofit TOS N/C milling machine, microcomputers, dynamometers, proximity probes, a vision system, and a laser interferometer used for machine accuracy determination.

II) Personnel Data

Principal Researchers:

Dr. D. Capson	Assistant Professor	Elec. Eng.
Dr. H.A. ElMaraghy	Associate Professor, Director CFMRD	Mech. Eng.
Dr. D. Ghista	Professor	Biochemical Eng.
Dr. R. Kitai	Professor	Elec. Eng.
Prof. W.R. Newcombe	Professor	Mech. Eng.
Dr. N. Sinha	Professor	Elec. Eng.
Dr. I. Yellowley	Associate Professor	Mech. Eng.

III) Research Activities

A Centre for Flexible Manufacturing Research and Development is being established at McMaster and will focus on flexible assembly operations which include the use of robots. The objectives of this new centre are: to conduct research on flexible manufacturing problems, to develop solutions for industry for problems in the area of flexible manufacturing, to develop human resources, to develop a test facility for prototype projects, and to establish a technological transfer mechanism. The Federal Government in August of 1984, under the Centres of Specialization Fund, provided a one year grant of $500,000 to launch the centre.

Presently, planning of the centre is being undertaken. Renovation of the area allocated for the centre will begin in April of 1985. Most of the $500,000 grant is allocated for the purchase of hardware, and a portion of this amount will be used for purchasing robotics-related equipment. The centre is expected to be in full operation by the second half of 1985.

Researchers of the university closely co-operate with the Canadian Institute of Metalworking (1276 Sandhill Drive, Ancaster, Ont. L9G 3N6).

Research interests cover a wide range of robot application areas including: sensor development, gripper design, kinematics, off-line programming, real-time adaptive control, computer vision, speech recognition and artificial intelligence. Interest is considerable in robotic assembly operations, inspection, and processing application areas such as welding, deburring, polishing, machine loading, object tracking, and system integration.

Some of the work currently being undertaken by Prof. Capson and Prof. Kitai is connected with developing hardware and software for a robot vision system for the recognition and locating of silhouette shapes. A binary vision system was developed for use by, and interfaced with, the Puma 600 robot for sorting operations. Solder joint inspection of PC-boards, and tracking of moving objects using a high speed vision system are other projects currently being investigated.

Prof. Sinha works on development of robot control systems for welding and other applications. Another of his topics is speech recognition for robots. A total of five graduate students are engaged, via the Electrical Engineering Department, in robotics-related projects. Results of most of this research has been published in conference proceedings and journals.

Prof. ElMaraghy's area of research is robotic expert systems for task planning, off-line programming, eye-hand co-ordination, and real time control with sensors. Prof. Yellowley's main interest is in the area of manufacturing and automation. He works on simulation and modelling of robot operation and application of robots for welding, grinding, polishing, deburring, machine loading, unloading and tool changing using robots. Motion planning using circular and polynomial interpolation has been developed. Seven graduate students are engaged in work in the area of robotics in the Mechanical Engineering Department. Research in most of these areas began recently; hence, publications are not yet available.

The principal objective of the research is to develop practical applications for robots as part of an integrated system. Development of a binary vision system, development of software routines and algorithms for programming, controlling and modelling of robots, and retrofitting robots are considered to be the major accomplishments to date.

IV) Bibliography

1. Capson, D., Pena, M. and Kitai, R., A Silhouette vision system for robots, Proc. of the Canadian Conference on Robotics, pp. 73-84, Sept. 1982.

2. Capson, D., Kitai, R., Silhouette area and centroid measurement using a CID camera and an 8086 Microcomputer, conf. proc.

3. Capson, D.W., An improved algorithm for the sequential extraction of boundaries from a roster scan, Computer Vision, Graphics and Images Processing, 28, pp. 109-125, 1984.

QUEEN'S UNIVERSITY

Queen's University Robotics Laboratory

Kingston, Ontario
K7L 3N6

Professor M. M. Bayoumi
(613) 547-2878

I) Site Data

Robotics research at Queen's is conducted primarily in the Queen's University Robotics Laboratory (QURL). The Laboratory was established in 1983 following work on robotics simulation and adaptive control initiated in Electrical Engineering in 1980. Subsequent expansion included researchers and facilities in Computing and Information Science, Psychology and Mechanical Engineering.

The equipment associated with QURL includes: a PUMA 550 robot, a Sensoflex tactile array, an ultrasonic ranging system, an OMRON fibre photo switch, and Matrox and Norpack frame buffers. Computational support includes: a VAX 11/780 and PDP-11/23 computers, a symbolic 3600 Lisp machine, a National 32016 work station, 3 Intel 310 systems, an AED-767 graphics display and a Wertek Array Processor.

Funding sources include: NSERC through operating and PRAI grants, Health and Welfare Canada, BILD, Alcan and Intel.

II) Personnel Data

Principal Researchers:

M.M. Bayoumi	Director, Professor	Electrical Engineering
R. Browse	Assistant Professor	Computing & Information Science
J. Jeswiet	Associate Professor	Mechanical Engineering
J. Kulick	Assistant Professor	Computing & Information Science
S. Lederman	Associate Professor	Psychology
G. MacEwen	Professor	Computing & Information Science
T. Moore	Assistant Professor	Mechanical Engineering

In addition, associated with QURL, there are 2 technical staff members and 19 graduate students, 10 in Computing and Information Science, 5 in Electrical Engineering, 2 in Mechanical Engineering and 2 in Psychology.

III) Research Activities

The principal objectives of QURL activities are directed toward multi-sensor robotic perception, integrated robotic software environments and planning and control systems.

Areas of research include: computational perception and touch (Browse), sensor/gripper development (Moore, Bayoumi), real-time software (McEwan), high-level robotics languages (McEwan), tactile perception (Lederman), industrial inspection (Bayoumi), adaptive control (Bayoumi), dynamic modelling and control (Bayoumi), and collision avoidance (Bayoumi).

Image Processing and Computational Perception

Image processing and computational perception research at Queen's University spans a wide variety of specific topics under investigation in the Departments of Computing and Information Science, Electrical Engineering and Psychology. While the motivations differ across these disciplines, a common requirement for a computational basis for perceptual processes has led to a constructive interaction among researchers in such seemingly disparate disciplines as real-time robotics and psychological modelling. There are several indications that this interaction will continue to expand in the near future. Construction begins this year on a new Technology Center at Queen's, which will have the effect of bringing researchers in robotics, image processing and artificial intelligence into close physical proximity. A subject of specialization B.Sc. programme in Cognitive Science has recently been established and the formation of a Cognitive Science and Robotics group, which will be able to develop interdisciplinary graduate study programmes, is expected soon.

The objectives of this project are to develop effective techniques for the representation and application of knowledge of objects in visual interpretation. Experimental computational vision systems have been implemented which demonstrate: intelligent selection of image processing locations in response locations in response to the status of interpretation operations, interaction among interpretations based on separate levels of resolution, relations between the constraints of abstract geometric models of objects and the constraints inherent in image information. Computational versions of psychological theories of visual perception and interpretation have been devised. The group is involved in ongoing experimentation with human subjects in an attempt to understand the processes of vision more fully, and to assist in the refinement of their computational models.

A research goal is to devise a theoretical groundwork for the development of robots which are capable of understanding their environment and modifying their actions to adapt to their surroundings. To this end, initial concern is

with tactile perception and organizing kinesthetic information. The long term goal is to permit integration across sensory inputs, including vision, using unified object model representations. Software has been developed to operate a touch sensing device capable of returning a 16 × 16 pressure profile across a square inch of surface. Image processing and surface recovery techniques have been adapted to operate over these pressure images. A system has been developed which is capable of the recognition of objects and their position based on the extracted properties of the tactile images. Human experiments have been carried out which indicate availability and usefulness of touch features. These indications are currently being considered in extensions to the computational touch system. Computational models have been devised to represent the constraints imposed on object identity through grasping.

A corresponding line of human experimentation is being pursued. Perceptual organization in vision may be seen as the process of making explicit certain relationships or regularities among image properties. These relationships may then be explained by subsequent interpretive process. The general theoretical questions that are addressed involve the nature of the processes and rules governing the organization of images and the nature of the resulting representations (or descriptions). The major part of this project involves experimentation with humans aimed at the definition of the mathematical properties of global perception. Particular interest lies in developing a mapping between these computed descriptions and constraints on the interpretation of events.

A project has recently been initiated with ALCAN International, on the development of computer techniques for analysis of micrographs of aluminum alloys. At present, a trained microscopist must look at each image, and decide which processing technique (heating, rolling, ...) should be applied next. Mathematical descriptions of the images are being developed which permit the processing to be automated. The long term goal is to develop shape descriptions which have direct correspondence to the underlying mechanical properties of the materials. Images are processed by a light weight camera mounted on a PUMA-550 robot arm. Geometrical features are extracted, including center of gravity and moments of inertia along the principal axis. This information is processed by different tracking algorithms including one that is based on the Kalman filer. One objective of the project is to integrate the results of the image processing with the robotic arm movement to achieve tracking behaviour.

Research Projects:

Surface Characteristics from Touch Sensed Data

With the use of a protopype touch sensing device obtained from Barry Wright Corp. (Sensoflex Tactile System), methods are being developed for the recovery of surface information from a 16 × 16 × 8 bit array representing a pressure profile within a square inch. The confound of factors contributing to this pressure profile is analogous to those involved in the image formation

equation (Horn, 1977) in computational vision. Following initial testing and calibration, the touch sensing system will be mounted on the PUMA-550 in the Electrical Engineering Department's Robotics Laboratory.

R. Browse (Computing and Information Science & Psychology)
S. Lederman (Psychology)
S. Ulug (Computing and Information Science) (graduate student)

Computational Models of Intersensory Integration

The goal of this project is the development of techniques for the representation of object knowledge which is capable of dealing with constraints imposed by visual, proprioceptive (joint position), and touch sensed data. The problems of an active multimodal robot in a dynamic planning environment are addressed. Experimental work with humans is also being carried out.

S. Lederman (Psychology)
R. Browse (Computing and Information Science & Psychology)
B. Jones (Psychology: Carleton University)
J. Rodger (Computing and Information Science) (graduate student)

The Features Used in Human Touch Perception

The techniques used in Feature Integration Theory experimentation (Treisman & Gelade, 1980) are being extended to examine touch-based features. One important goal in this work is to determine independence (Garner, 1978) and utility of features such as roughness, temperature, orientation, and scale, in order to lay the groundwork for a computational model of touch perception for robotic devices.

S. Lederman (Psychology)
R. Browse (Computing and Information Science & Psychology)

Parallelism in Perception

In this project, an attempt is made to identify the nature of parallelism involved in major psychological theories of perception. These versions of parallelism are compared to the models proposed in the artificial intelligence literature (such as Ballard & Feldman, 1982; Fahlman, 1979). As well, the feasibility of their implementation in specialized parallel processing hardware is examined.

R. Browse (Computing and Information Science & Psychology)
S. Lederman (Psychology)
R. Van Veen (Electrical Engineering) (graduate student)

(title unknown)

This project studies the capabilities and strategies involved in human identification of 3-D objects through grasping. The aim is to represent the actions involved in tactual interpretation in a body-connected coordinate system in order to develop a computational model of this behaviour.

S. Lederman (Psychology)
R. Browse (Computing and Information Science & Psychology)
R. Klatzky (Psychology: U. California at Santa Barbara)
L. Lambert (Psychology) (graduate student)

Control Systems for Robots Capable of Sensing

This project centers on the development of a controller for the PUMA-550 which is capable of incorporating highly structured sensory information. The system will offer software which may be used to express task-specific utilization of sensory information.

M. Bayomi (Electrical Engineering)
R. Browse (Computing and Information Science & Psychology)
B. Mack (Electrical Engineering) (graduate student)

Human Tactile Texture Perception

A sensory model of the tactile perception of surface texture by humans has been developed and experimentally evaluated using psychophysical methods

S. Lederman (Psychology)
J. Loomis (Psychology: U. California at Santa Barbara)

Programming Languages for AI, Robotics, and Vision

Robots capable of multimodal sensing and dynamic planning will present unusual requirements for the next generation of artificial intelligence programming languages. In particular, the software will be required to express concurrency, "spatial" parallelism, and logical inference. Towards this goal, experimentation with the language NIAL (Jenkins, 1983) and its extensions, which include logic programming capabilities, is being performed. The array primitive and the sound mathematical foundation of the language make it a fine candidate for robotic programming (see Glasgow & Browse, 1984).

M. Jenkins (Computing and Information Science)
J. Glasgow (Computing and Information Science)
R. Browse (Computing and Information Science & Psychology)
N. Cercone (Computer Science: Simon Fraser University)
C. McCrosky (Electrical Engineering & Computing and Information Science) (graduate student)
E. Blevis (Computing and Informations Science) (graduate student)

Mediation Between Image-based and Object-based Constraints

Control mechanisms for computational vision systems have been devised which are capable of mediation between constraints imposed by dealing with a class of specific objects, and those constraints inherent in the image due to general assumptions about imaging conditions and surface properties. Experimentation with the first implemented version demonstrates an ability to deal with an extensive range of imaging conditions.

R. Browse (Computing and Information Science & Psychology)
R. Gurnsey (Computing and Information Science & Psychology) (graduate student

Tactual Processing of 2-D Patterns

These studies are designed to understand the tactual perception of small scale spatial layouts, including raised maps and pictures. Systematic errors in spatial judgement reflect human strategies and, as well, suggest tangible graphics for the visually impaired.

S. Lederman (Psychology)
R. Klatzky (Psychology: U. California at Santa Barbara)
P. Barber (Psychology) (graduate student)

IV) Bibliography

Publications related to robotics research include 3 MSc theses, 8 refereed papers, and 5 papers submitted. A sample of these is given below.

1. Bayoumi, M.M., Chan R.T.F., Model following control of manipulators, accepted for publication in Digital Systems for Industrial Automation.

2. Browse, R.A., Computational selection of processing location in vision, Proc. Fifth Annual Conference of the Cognitive Science Society, Rochester, New York, 1983.

3. Klatzky, R.L., Lederman, S.J., Metzger, V. Identifying objects by touch, accepted for publication in Perception and Psychophysics, 1985.

4. Moore, T. A health monitoring system for robots, 6th International Symposium on Robotics and Automation, Santa Barbara, Cal. May 1985.

The bulk of the literature (co)authored by Dr. S. Browse and/or Lederman deals with biological/computional vision and biological tactual perception, respectively. For this reason, this literature is not presented here.

TORONTO, UNIVERSITY OF

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I) Site Data

History of Growth:

The Robotics and Automation Laboratory is a research lab within the Department of Mechanical Engineering at the University of Toronto. It was established in September 1982 under the direction of A.A. Goldenberg who joined the Mechanical Engineering department, having completed one year of University Research Fellowship at the U of T's Department of Electrical Engineering. Prior to joining the Electrical Engineering faculty, and following his doctoral research in control systems at the U of T, Goldenberg was an employee of Spar Aerospace Ltd. Co-directing RAL is R.G. Fenton, a professor with the U of T's Department of Mechanical Engineering.
The primary objectives of RAL are as follows:

- advance fundamental research in the science of robotics and automation with emphasis on automated manufacturing
- undertake industrial research, development and consulting contracts
- educate engineers - at the undergraduate and graduate levels - on the topics of robotics and automation

Facilities:

Facilities available to RAL researchers consist of:

robots:	IBM-7565, IBM-7545, Unimation Puma-560, Rhino-XR2, Rhino Scorpion, VSI Automation Charley 2
vision systems:	Octek 2200 (16 level, PDP-11/73 host), IRI P256 (256 level, stand-alone)
computers:	PDP-11/73 (11/23), MSP-300 array processor, Apple-II, IBM-PC, IBM-Series 1, VAX 11/750

other: computer peripherals, video recording equipment, CAD workstations

All of this equipment (except for the VAX 11/750 and CAD workstations) is within RAL's approximately 800 sq. ft. of floor space which is divided into undergraduate, office and research areas.

Affiliations:

RAL's principal affiliation is with the Department of Mechanical Engineering. However, through joint graduate and undergraduate projects, RAL also maintains connections with the Departments of Electrical Engineering and Computer Science. In addition, the new CAM option being offered by the Department of Engineering Science will affiliate the lab with the departments of Industrial, Metals and Material Science, and Chemical Engineering.

Source(s) and amounts of funding:

RAL received start-up funding from the University of Toronto's Faculty of Applied Science and Engineering and from the Department of Mechanical Engineering ($223,000). In addition, funding is available through operating, strategic and equipment grants. A list of grants which have been awarded follows. It should be noted that, in some major grant applications, the principal applicant (A.A. Goldenberg) and co-applicant (R.G. Fenton) have been supported by staff from other departments (H.W. Smith and K.C. Smith - Electrical Engineering, J. Buzacott - Industrial Engineering, J. Tsotsos - Computer Science).

Grants awarded:

Grant	Tenure	Applicant	Title
NSERC-operating	81/84	A.A. Goldenberg	Control of Industrial Automation
Bickell Foundation-operating & equipment	83/84	A.A. Goldenberg	Integrated Sensory System for Robotic Manipulators
BILD-equipment	83/84	A.A. Goldenberg and co-investigators (R.G. Fenton, K.C. Smith, H.W. Smith)	Robotic Based Automated Manufacturing Systems

NSERC-strategic-operating	84/86	A.A. Goldenberg and co-investigators (R.G. Fenton, K.C. Smith, J. Buzacott)	Robotic Based Integrated Industrial Automation
NSERC-operating	84/87	R.G. Fenton	Design, Robotics & Manufacturing
NSERC-operating	84/87	A.A. Goldenberg	Robotics Based Integrated Industrial Automation
U of T-Small Grants	81/84	A.A. Goldenberg	Robotics Laboratory-operating and equipment
Northern Telecom Inc.	84/85	A.A. Goldenberg	Automated Light Manufacturing
NSERC-equipment	84/87	A.A. Goldenberg (minor user) (principal investigator - J. Tsotsos of Computer Science Dept.)	LISP Machine
NSERC-New Research Idea	85/86	A.A. Goldenberg & R.G. Fenton	Tactile Sensing Multi-finger Hand (equipment)
			Total $672,000

For fiscal 84/85, RAL's operating expenses total approximately $300,000. Funding for this amount is covered by research grants and contract research fees.

In addition to grant-supported research, RAL performs research on a contract basis. This contract research is important for generating research funding and for establishing credibility. Since 1982 research contracts totalling $418,000 have been undertaken with NRC, Ministry of Transportation & Communication of Ontario, Northern Telecom Ltd., IBM of Canada Ltd., Vadeko International Inc., and Ontario Hydro. The topics of work included: robot-based manufacturing, non-real-time and real-time simulation, and robotic mobility. In total, since the establishment of the laboratory (Aug. 1982), the revenues (start-up fund, grants & contracts) have totalled over $1.3 M.

Fee structure and external services:

The laboratory fees for services are based on U of T regulations for professional consulting services. The laboratory research engineering's services are based on an average income of $40,000/year. For graduate students, services are renderable at the rate of $960/mo. For machinery and equipment fabrication the fees are set by the departmental machine shop's supervisor, Mr. P. Loite.

Clientele:

The facility can be rented by outside users for nominal fees. In addition, university staff from other departments may use the equipment. Present clientele includes: IBM of Canada, Northern Telecom, Ontario Hydro, Ministry of Transportation & Communications and others.

Projects suggested by outside agencies are reviewed as to their relevancy to the mandate of RAL.

Plans for Expansion:

In the near future, the laboratory will expand with additional floor space and with the acquisition of new equipment. The equipment will include a workstation, a minicomputer, facilities for performing research on the multifingered hand and on a flexible 2-DOF arm.

During 1986 the Laboratory will become part of the University of Toronto Centre of CAD/CAM & Robotics. The Centre will consist, in the initial phase, of RAL and the Computer-Aided Engineering Laboratory. This centre will be located in a new facility on the campus.

II) Personnel Data

Director:	A.A. Goldenberg	Mech./Elec. Engineering
Faculty:	R.G. Fenton	Mechanical Engineering
Affiliated Faculty:	A. Sinclair	Mechanical Engineering
	H.W. Smith	Electrical Engineering
	K.C. Smith	Electrical Engineering
	J.K. Tsotsos	Computer Science
Staff:	R.A.D. Wallace	Research Eng. - Electrical
	J. Wiercienski	Research Eng. - Mechanical
Affiliated Staff: (part-time)	B. Benhabib	PhD student - Mech. Eng.
	I. Jhajj	M.A.Sc student - Mech. Eng.
	A. Kuo	undergrad. student - Mech. Eng.
	J. Mills	PhD student - Mech. Eng.
	B. Sooley	consultant - electrical
	A. Melidy	consultant - software

In addition, 15 graduate students (2 PhD, 9 MASc, 2 M Eng from Mech. Eng and 2 from Elec. Eng.) are presently supervised by Professors Goldenberg and Fenton. Undergraduate students are also supervised (3 in 1982, 8 in 1983, 10 in 1984, 25 presently) and conduct robotics research to satisfy thesis requirements.

III) Research Activities

The research areas of the laboratory staff and affiliated students are summarized as follows:

Kinematics (A.A. Goldenberg and R.G. Fenton)

In the context of kinematic control of robotic manipulators, Goldenberg and Lawrence have developed an iterative inverse kinematics algorithmic solution for six degrees of freedom (DOF) manipulators, which introduced the residual displacement concept. Following this work, Goldenberg, Benhabib and Fenton developed a generalized iterative solution which is suitable for any class of robots with arbitrary types of joints and numbers of DOF. The new method is based on a rapidly convergent constrained optimization algorithm using a modified Newton-Raphson technique.

Control of kinematically redundant robots, achieved by newly developed inverse kinematics methods, has been demonstrated in the Ph.D. thesis of Benhabib (co-supervised by Fenton & Goldenberg).

End effector Continuous Path (CP) planning algorithms which employ piecewise polynomial interpolation between trajectory points result in efficient control schemes. The work reported by Goldenberg and Lawrence on the end-effector trajectory planning, by interpolating between Cartesian end-effector locations, was further developed by Benhabib. The new algorithm incorporates a constrained optimization technique to determine an optimal set of time intervals when interpolating cubic polynomials between the trajectory points.

More recent work by Benhabib on off-line CP trajectory planning explored new algorithms to optimize the end effector's motion for redundant robots. A two-level optimization algorithm developed by Benhabib minimizes deviation from a specified trajectory in 3D space using the redundant DOF's of the robot as constrained variables. A natural extension of this technique was the selection of a minimal number of locations in order to approximate a bounded trajectory.

Control (A.A. Goldenberg)

In assembly operations, the robot motion is constrained by the task geometry and is termed compliant motion. A method of force feedback which is based on servo-loop compensation has been examined in Bazerghi's thesis. This method controls the compliant motion actively using task space contact sensors and a mathematical model of the robot. The algorithm has been applied to a simulated 'peg-in-hole' rigid insertion task.

A new method based on 'preview' control of the compliant motion was developed by Goldenberg. This approach predicts the forces generated on the contact points of mating parts. An approach to control of robots based on robust compensators was also introduced by Goldenberg. The approach, which used the computed torque method, is suitable for designing robust compensators. The method expands earlier published results by removing the assumption that the computed elements of the model are identical to their actual counterparts.

A new kinematics control method is reported by Apkarian's M.A.Sc thesis. The new method also compensates for errors due to unknown loading. This non-linear adaptive control scheme eliminates the need for kinematics and dynamics modelling of the robot by identifying the linearities, as well as the non-linearities, about the nominal trajectory using a recursive Least-Squares estimator.

Design of controllers using the computed torque technique for light-weight single-link robot with structural flexibility has been developed in Rakhsha's thesis. The method uses known techniques of dynamics modelling (used for aerospace applications) and demonstrates that by using the computed torque method based on the rigid body model, a faster response is obtained. Dharna's M.A.Sc. thesis implements a synthesis procedure for developing, via state feedback, a six DOF robot (PUMA-560).

New research is underway on a new approach to real-time control of robots in task space using force and tactile sensors. A method for adapting existing software and hardware in order to accomplish task space control is being pursued by Malidy and Cai Long. This scheme is being implemented with the aim of producing a new controller for the PUMA-560 robot for operation without VAL.

Simulation (A.A. Goldenberg and R.G. Fenton)

An extensive simulation program for (rigid-body) robotic manipulators was developed by Goldenberg. This program contains five modules: main, kinematics, control, dynamics and utilities. The program, which can be used to simulate in non real-time any robot motion with commands in task space, was successfully utilized for the PUMA-560 robot. Further work reported in Bazerghi's thesis includes a mathematical model which accomodates an efficient simulation algorithm for the calculation of forces for a six DOF robot performing a 'peg-in-hole' rigid insertion.

Rakhsha addressed the design of controllers for single-arm robots with structural flexibility. The new interactive simulation algorithm determines the dynamic response of the arm under the 'Computed Torque' technique. Further work is now in progress on dynamic modelling of two-link robot arms with structural flexibility.

Graphics-based computer simulation programs are valuable to robotics research. The interactive animation program developed by Benhabib simulates the robot motion in 3D for workcell layout and detection of collision. Kuo's thesis utilizes the IBM/CATIA software package to model the 3D workcell and robot structure and to animate, in non-real-time, the motion of the robot.

Assembly Automation (A.A. Goldenberg and R.G. Fenton)

Industrial competition and productivity gaps between leading industrialized nations and Canada are major national concerns. A study on automatic assembly in manufacturing, performed by Serles and Goldenberg, outlined current approaches to automatic assembly and research topics relevant to this area.

In the laboratory, several studies and implementation of a variety of robotic-based automation applications has been undertaken. These include: Payanden's heat-sink project in which a SCARA robot workcell is presented with integrated circuits and heat-sinks and produces sink-mounted chip assemblies, and a variety of undergraduate thesis projects which utilize the IBM 7545, PUMA-560 or CHARLEY 2 robot for automatic assembly processes.

J. Wiercienski and A. Goldenberg have developed a conceptual design of an R & D facility for automatic assembly research. The project is currently being evaluated for hardware commissioning.

Design Optimization (R.G. Fenton)

The configuration of a robot and the size of its members determine the robot's workspace and also have influence on the cycle-time and dynamic effects during the performance of tasks. A selection procedure of the robot's configuration dimensions, based on a systematic optimization technique, was developed by Lipitkas and Fenton. This efficient algorithm optimizes an objective function which is the weighted average of several functions including the workspace volume and the average cycle-time. Lipitkas has completed the research for his M.A.Sc., implementing this optimization algorithm to verify optimal dimensions for the PUMA-560 and the Elbow-manipulator robots.

Further work is ongoing with Zbroja on the development of an interactive optimization scheme of the robot's configuration considering the non-linear dynamic properties. Various objective functions are being formulated for application to industrial robots.

Accuracy and Repeatability (R.G. Fenton)

Accuracy, repeatability and resolution are important parameters for robots operating under stringent tolerances. A test procedure that can be performed with simple measurement instruments (dial indicators) was developed in Davison's thesis. A further study undertaken by Fenton resulted in the development of various techniques which could be used to test an industrial robot's accuracy and repeatability. This work, which investigated some of the fundamental difficulties of robot testing, may provide a foundation for standardization of accuracy and repeatability testing of industrial robots. Some of the methods introduced by Fenton have successfully been demonstrated by testing the accuracy and repeatability of a PUMA-560 robot.

Articulated Multi-finger Gripper (A.A. Goldenberg, J. Wiercienski)

Current end-effectors have limited flexibility and applicability to

arbitrary part handling and sensing. Increasing use of industrial robots in manufacturing, especially in assembly, necessitates a mechanical 'copy' of the human hand, which would ease handling of parts regardless of shape and weight. In the laboratory the design of a four-finger mechanical hand is being undertaken by Wiercienski. The configuration allows irregular objects to be grasped both externally and internally.

Two different mechanical concepts were pursued for the analysis and development of mechanical fingers by Wiercienski. The first finger, manufactured in our machining centre and assembled in our laboratory, is actuated by means of two opposing tendons. The tendons are symmetrically interlaced around rollers and actuated by a single motor.

The second design incorporates a lead-screw in each joint (3) which is connected, via a flexible shaft and a magnetic clutch, to a single stepper-motor. The joints of the fingers can bend in both directions by alternately changing the rotation of the motor. This design is being incorporated into the 'mechanical hand'.

The control of the proposed multi-finger gripper involves the coordination of fifteen DOF's. The methodology is to consider the hand as a kinematically redundant system and optimize finger-motions by defining task dependent performance criteria.

At the present stage of gripper development, emphasis is being placed on sensing and control.

Tactile Sensing (A.A. Goldenberg, R. Wallace)

Tactile sensing research is being undertaken with the aim of providing this sense capability to Wiercienski's multifinger hand. Wallace produced a report which reviewed experimental and commercial tactile sensors in the course of selecting a research direction. He is presently investigating the use of the piezoelectric polymer polyvinylidene fluoride (PVF_2) as a tactile transducer and has produced an operational 2 × 4 and 4 × 4 array with this material. Research is presently addressing the areas of sensor construction techniques and signal processing while future research will be concerned with signal interpretation (i.e. interpretation of tactile "image").

Principal research objectives:

The research objectives of the laboratory are: i) to integrate contact sensing capabilities with robot control; ii) to develop systematic methods for the design of automatic-assembly turn-key systems; iii) to develop robots with mobility; iv) to develop generic end-effectors which may handle irregular parts; v) to develop light-weight robot arms.

Areas of specialization:

The laboratory specializes in i) integration and control of multidegree of freedom industrial automation; ii) kinematic control of robots; iii) control of flexible arms; iv) application and integration of sensors (contact or

non-contact) with robot; v) development of intelligent grippers for generic use. In terms of applications the laboratory specializes in automatic assembly, mobility for inspection and servicing, and high precision multidegree-of-freedom mechanisms.

Major accomplishments/developments to date:

RAL staff and affiliated students have many accomplishments to their credit to date, these being:

- Wiercienski and Goldenberg developed two fully functional, remotely-operated fingers. A fully mechanical hand is presently being developed which incorporates 4 of the modified prototype fingers.
- Wallace and Goldenberg developed a 2 × 4 and a 4 × 4 PVF_2-based tactile array which will be incorporated with the mechanical hand (fingers).
- Melidy and Goldenberg developed a new software control scheme for the PUMA-560 robot using the PDP-11/73 minicomputer.
- Benhabib, Fenton and Goldenberg have produced a complete generalized solution to the inverse kinematics of robots possessing an arbitrary number of degrees of freedom.
- Raksha and Goldenberg developed a new method for applying the computed torque technique to the control of flexible robot arms.

Major software programs either developed or used:

Developed:
- PUMA-560 Simulation (currently used at Concordia and McGill Universities)
- interactive inverse kinematics solution for an arbitrary number DOF robot
- formulation of force sensor for peg-in-hole insertion
- adaptive kinematic control algorithm
- real-time control of PUMA without VAL using PDP 11/73

Acquired:
- RCCL (Purdue University)

Parties with whom RAL communicates:

University links:

Electrical Engineering: H.W. Smith, E. Davison and K.C. Smith (co-supervision of graduate students and support for BILD, strategic, and New Research Idea grant applications)

Industrial Engineering: J.A. Buzacott and E.E. Pickett (support of BILD application)

Computer Science: J.K. Tsotsos (support of BILD and New Research Idea applications)

Outside University:

Professor A.A. Goldenberg has participated in some activities of the Canadian Institute of Advanced Research - Artificial Intelligence, Robotics and Society. He participated in the founding conference in Ottawa, March 1984, and presented an invited paper at the workshop on Artificial Intelligence in Vancouver, UBC, June 1984.

In addition, some contacts exist with the Computer Vision and Robotics Laboratory of the Department of Electrical Engineering at McGill University.

On the industrial scene, Professor A.A. Goldenberg maintains close contacts with: Northern Telecom Ltd.'s plants in Bramalea, London and Belleville, Ontario; IBM Canada, Don Mills; Ministry of Transportation and Communications, Downsview; Ontario Hydro; Vadeko International Inc., Mississauga; and the Ontario Robotic Centre, Peterborough, Ontario.

Following a series of visits to leading laboratories in the U.S.A., Professor Goldenberg maintains some contacts in the form of an exchange of reports with MIT's, Artificial Intelligence Laboratory; Charles Stark Draper Laboratory, Boston; Purdue University, Indiana; Rensselaer Polytechnical Institute, Troy, New York; University of Rhode Island and Carnegie-Mellon University, Pittsburgh.

Contacts have also been developed with the IBM Robot Manufacturing Division, Boca Raton, Florida, where Professor A.A. Goldenberg spent some time in 1983.

Position in robotics R&D community:

As a research, development and educational laboratory RAL's role is to provide expertise, facilities and general support in order to advance: i) fundamental work in the development of the science of robotics; ii) education of engineers; iii) collaboration with industry. The work in fundamental theory is essential to other research centres in Canada and abroad. RAL's objectives are to create theory, solve problems and test solutions on prototype hardware. The main industrial segments aimed at are manufacturing and servicing. The record, so far, has given Canada visibility in some areas of Robotics R&D.

Participation in the Joint Coordinating Forum on International Cooperation in Advanced Robotics:

The work on intelligent robot control, optimal design, contact sensing, flexible arms and mobility is currently the subject of intensive international and national interest in both university and industrial centres. RAL is prepared to support Canadian involvement through the Joint Co-ordinating Forum in these areas.

IV) Bibliography

Books:

Under contract with Reston Publishing Inc. to publish, in 1985, a book entitled "Introduction to Advanced Robotic Systems" (Goldenberg).

Journal Papers, Proceedings Papers (published in full, with review of complete paper):

1. Bazerghi, A., Goldenberg, A.A., Apkarian, J., An exact kinematic model of PUMA-600 robot manipulator, IEEE Transactions on Systems, Man and Cybernetics, Vol. 14, No. 3, pp. 483-487, May-June 1984.

2. Bazerghi, A., Goldenberg, A.A., Simulation model of insertion process, Robots 8, pp. 6.84-6.96, June 1984.

3. Benhabib, B., Goldenberg, A.A., A solution to the inverse kinematics of redundant robots, Journal of Robotic Systems, in print; also, American Automatic Control Conference, 1985.

4. Fenton, R.G., Benhabib, B., Goldenberg, A.A., Optimal point to point control of robots with redundant degrees of freedom, ASME Computer Integrated Manufacturing and Robotics, pp. 93-100, 1984; also Transactions of the ASME, Journal of Engineering for Industry, in print.

5. Goldenberg, A.A., Comment on a linear algebra approach to the analysis of rigid body velocity from position and velocity data, Transaction of the ASME, Journal of Dynamic Systems, Measurement Control, Vol. 106, No. 3, pp. 240, September 1984.

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7. Goldenberg, A.A., Lawrence, D., End effector path generation, ASME Sensors and Controls for Automated Manufacturing and Robotics, pp. 271-280, 1984,; also Transactions of the ASME, Journal of Dynamic Systems, Measurement, and Control, in print.

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10. Goldenberg, A.A., Robot gripper path generation, IFToMM on Design and Synthesis, pp. 697-702, July 1984.

11. Goldenberg, A.A., Bazerghi, A., Synthesis of robot control for assembly processes, Journal of Mechanism and Machine Theory, in print.

12. Goldenberg, A.A., Bazerghi, A., A preview approach to force control for robot manipulators, Journal of Mechanism and Machine Theory, in print.

13. Goldenberg, A.A., Rakhsha, F., Dynamic modeling of a single link flexible robot, IEEE Robotic Research and Automation, 1985, in print.

14. Goldenberg, A.A., An AML implementation of IBM-7565 robot kinematic and dynamic simulation, Journal of Robotic Systems, in print.

15. Goldenberg, A.A., Benhabib, B., Fenton, R.G., A complete generalized solution to the inverse kinematics of robots, IEEE Journal of Robotics and Automation, in print.

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Papers submitted for Journal Publication (currently under review):

1. Apkarian, J., Goldenberg, A.A., Smith, H.W., A new approach to kinematics control of robot manipulator, IEEE Journal of Robotics & Automation.

2. Apkarian, J., Goldenberg, A.A., Smith, H.W., A new approach to kinematic & Dynamic control of robot manipulator, Transactions of the ASME, Journal of Dynamic Systems, Measurement of Control.

3. Benhabib, B., Goldenberg, A.A., Fenton, R.G., A solution to the inverse kinematics of redundant robots, Transactions of the ASME, Journal of Dynamic Systems, Measurements and Control.

4. Benhabib, B., Goldenberg, A.A., Fenton, R.G., Optimal path generation for redundant robots, Transactions of ASME, Journal of Engineering for Industry.

5. Goldenberg, A.A., A. Melidy, G. Suwala, An approach to real-time control of robots in task space application to PUMA-560 control without VAL, IEEE Transactions on Industrial Electronics.

6. Goldenberg, A.A., Robust control of robot manipulator, IEEE Transactions on Automatic Control.

7. Goldenberg, A.A., Contribution to synthesis of manipulator control, Journal of Robotic Systems.

8. Goldenberg, A.A., Control of robot with disturbance rejection, Journal of Robotic Systems.

9. Goldenberg, A.A., Benhabib, B., End effector optimal path generation, IEEE Transactions on Systems, Man and Cybernetics.

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11. Rakhsha, F., Goldenberg, A.A., Feedforward control of a single-link flexible robot, Journal of Mechanism & Machine Theory.

12. Wallace, R.A.D., Goldenberg, A.A., A modular tactile sensor for robotic applications, Journal of Manufacturing Systems.

Papers Currently in Preparation for Journal Submission:

1. Benhabib, B., Goldenberg, A.A., Fenton, R.G., End effector trajectory generation using velocity profile.

2. Goldenberg, A.A., A new approach to kinematic modeling of robot Manipulators.

3. Goldenberg, A.A., Dharna, H., Davison, E.J., Adaption of Freunds's method for decoupling control of robots.

Conference Papers (published in full or accepted for publication in full with review by abstract only):

1. Benhabib, B., Fenton, R.G., Goldenberg, A.A., Point to point control of seven degrees of freedon robots for assenbly operations, Proceedings of 3rd Canadian CAD/CAM and Robotics Conference, pp. 10.1-10.8, June 1984.

2. Benhabib, B., Goldenberg, A.A., Fenton, R.G., Issues on motion analysis and kinematic control of redundant robots, 4th Canadian CAD/CAM and Robotics Conference, June 1985, in print.

3. Davison, T.J., Fenton, R.G., Goldenberg, A.A., Accuracy and repeatability of robots and manipulators, Advances in Robotics and Automation, pp. 126-128, 1984.

4. Fenton, R.G., Benhabib, B., Goldenberg, A.A., Performance evaluation of seven degrees of freedom robots, Advances in robotics and Automation, pp. 152-155, 1983.

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9. Goldenberg, A.A., Sharpe, A., Control of a large class of flexible systems, Proceedings of the Third Symposium on Large Spacecraft Structures, Blacksburg, Virginia, June 1981.

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11. Goldenberg, A.A., On the interactive design of robotic manipulator control, Proceedings of 22nd CDC Conference, pp. 1227-1232, December 1983.

12. Goldenberg, A.A., Apkarian, J., Non-linear adaptive torque control of three link manipulator. Proceedings of IEEE - Cybernetics and Society, pp. 43-48, New Delhi, January 1984.

13. Goldenberg, A.A., Dharna, H., Decoupling control of a robot manipulator application to PUMA 560, Proceedings of 7th Symposium on Engineering Applications of Mechanics, pp. 13-21, Toronto, June 1984.

14. Goldenberg, A.A., Sooley, B., A microprocessor based sign making robot, Proceedings of International Conference on Machine Control Systems, Brighton, U.K., October 1984, in print.

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16. Goldenberg, A.A., Wiercienski, J., A multifinger ariculated hand, Proceedings of 2nd Canadian Conference on CAD/CAM, May 1985, in print.

17. Goldenberg, A.A., A look-ahead approach to control of robot in assembly Operations, Proceedings of IFAC Conference, Peking, China, August 1985, in print.

18. Goldenberg, A.A., Off-line simulation of robot using interactive graphics, Proceedings of AUTOMACH, in print.

19. Goldenberg, A.A., Rakhsha, F., Simulation model for structurally flexible industrial robot, International Conference on Industrial Process Modeling, Zhejiang University, China, June 1985, in print.

20. Goldenberg, A.A., Rakhsha, F., Interactive kinematic simulation of robot, 1985, ASME International Computers in Engineering Conference, Boston, in print; also CIME.

21. Goldenberg, A.A., Melidy, A., A method for PUMA-560 operation without VAL, Robots 9, June 1985, in print.

22. Goldenberg, A.A., Rakhsha, F., Hybrid robot for assembly operations, 10th CANCAM, June 1985, in print.

23. Lawrence, D.D., Goldenberg, A.A., An efficient algorithm for the inverse kinematic solution of a manipulator, Proceedings of Optimization Days, pp. 30-31, Montreal, May 1983.

24. Rakhsha, F., Goldenberg, A.A., Control of one DOF robotic manipulator with structural flexibility, Procedings of Western Michigan Conference on Mechanical Engineering, October 1984, in print.

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26. Wallace, R.A.D., Goldenberg, A.A., A tactile sensor incorporating PVF_2 as the transduction medium, 8th International Conference on Production Research, Stuttgart, August 1985, in print.

Lab Reports/Proposals:

1. Goldenberg, A.A., Software development for simulation of a robotic manipulator - mathematical model, NRC Report, December 1982.

2. Goldenberg, A.A., Software development for simulation of a robotic manipulator - software documentation, NRC Report, December 1982.

3. Goldenberg, A.A., Robotic Applications for Future Go-Train, Ministry of Transportation and Communications of Ontario, February 1984.

4. Goldenberg, A.A., Serles, C., Automatic assembly in manufacturing. issues and a literature review, Technical Report TP83-7, University of Toronto, Department of Mechanical Engineering, May 1983.

5. Goldenberg, A.A., Wallace, R.A.D., Tactile Sensors for Robotic Applications - Review and Proposal, April 1984. Revised August 1984.

6. Goldenberg, A.A., Wallace, R.A.D., Proposal for a Tactile Sensor Incorporating PVF_2 as the Transduction Medium, August 1984.

7. Goldenberg, A.A., Wiercienski, J., Wallace, R.A.D., Tactile Sensing Articulated Multifingered Hand, December 1984.

8. Fenton, R.G., Accuracy and Repeatability of Robots, November 1984.

9. Melidy, A., Goldenberg, A.A., Real-Time Control of PUMA Without VAL, Part I: System Configuration; Part II: Description of Software, January 1985.

10. Wiercienski, J., Goldenberg, A.A., Pilot R&D Facility for Robot Assembly Cell, December 1984.

11. Reports on classified work for IBM of Canada Ltd., (3 reports).

12. Reports on classified work for Northern Telecom of Canada Ltd., (3 reports).

13. Reports on classified work for Vadeko International Inc. (3 reports).

14. Reports on classified work for High Productivity Robots Inc. (1 report).

15. Reports on classified work for Rothman's Pall Mall of Canada Ltd. (1 report).

Theses:

1. Apkarian, J., "Non-linear adaptive control of dynamics and kinematics of robot manipulators" (M.A.Sc. 1983).

2. Bazerghi, A., "Control of a robot manipulator in automatic assembly" (M.A.Sc. 1984)

3. Dharna, H., "Application of decoupling control to robot manipulators" (M.A.Sc. 1985)

4. Lipitkas, J., "Computer aided optimization procedure for the design of manipulator arms" (M.A.Sc. 1984)

5. Rakhsha, F., "Dynamic modeling and control of one-link flexible robot" (M.A.Sc. 1984)

6. Reeder, J., "Development of a compensating algorithm for static load and thermal deflection in manipulators" (M.A.Sc. 1984)

7. Sooley, B., "Development of a low cost vision system for industrial application" (M.A.Sc. 1984)

Theses in Preparation:

1. Benhabib, B., "Kinematics of Redundant Manipulators" (Ph.D. 1985).

2. Mills, J., "Dynamic Control of Robot with Parameter Perturbations", (Ph.D. 1986).

3. Bummbaca, F. "Vision System for Part Identification" (M.A.Sc. 1985). EE student; primary supervision K.C. Smith .

4. Fletcher, A., "Automatic Design and Manufacture of Molds for Dental Industry" (M.A.Sc. 1986).

5. Illiescu, V. "Static of Dynamic Reflection Compensation for Elastic Robots" (M.A.Sc. 1986).

6. Kozak, R. "Optimization of Work Envelope of Robots" (M.A.Sc. 1985).

7. Long, Cai, "Determination of Object Shape using Tactile Sensing" (M.A.Sc. 1985).

8. Payandeh, S., "Screw Axis Theory for Kinematic Modeling and Control" (M.A.Sc. 1985).

9. Schucka, A., "Compensation for Backlash in Precision Mechanisms" (M.A.Sc. 1986).

10. Stech, M., "Accuracy and Repeatability of Robots" (M.A.Sc. 1985).

11. Suwala, G. "Real-Time Control of Robots" (M.A.Sc. 1985). EE student; primary supervision K.C. Smith .

12. Woods, B., "Kinematics of Multifingered Hand" (M.A.Sc. 1985).

TORONTO, UNIVERSITY OF

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I) Summary

Robotics-related research in Electrical Engineering at the University of Toronto proceeds at two levels, externally via a strong coupling to the Robotics and Automation Laboratory in Mechanical Engineering and to the Computer Systems Research Institute, and internally, on an individual and ad-hoc group basis. Work directly relevant to robotic systems has been on-going since about 1980.

II) Personnel Data

Principal Researchers:

Dr. E.J. Davison	Professor	flexible space structures
Dr. R.H. Kwong	Assoc. Professor	flexible arms
Dr. H.W. Smith	Professor	manipulator control
Dr. K.C. Smith	Professor	sensors, human factors
Dr. A.N. Venetsanopoulos	Professor	image processing
Dr. W.M. Wonham	Professor	flexible manufacturing

Among the students currently supervised, there are 11 working in the general areas of interest.

III) Research Activities

Areas of research include: real-time image processing (Venetsanopoulos), modelling and control of flexible structures (Kwong, Davison), video-based senor systems (K.C. Smith), the human interface to computer-based systems (K.C. Smith), touch-tablets and sensors (K.C. Smith), coordinated discrete systems (Wonham) and flexible manufacturing systems (Wonham).

Areas of specialization include: human factors, image processing, control systems modelling, and control theory for discrete system coordination.

Major accomplishments to date include: the development of a test bed for space-based flexible arm development, the design of a recognizer for randomly-located colour-coded components, and a process for landmarking constrained scenes.

Strong interactions exist, through individual researchers, with the Robotics and Automation Laboratory in Mechanical Engineering and with the

Dynamic Graphics Group and Artificial Intelligence Group in the Computer Systems Research Institute. As well there are relationships with the University of Florence, Department of Electronics, and Imperial College, Department of Electrical Engineering.

Funding sources include NSERC, through operating grants, as well as Department of Communications, BILD, STM and Ford.

IV) Bibliography

Publications related to Robotics research include 11 MASc theses, 12 refereed papers and 5 papers submitted. A sample of these is provided below:

1. Davison, E.J., Control of automobile engines and flexible manufacturing assembly lines, Ford Motor Co., Dearborn, Michigan, Research Contract (2 year), Final Report, Feb. 1984.

2. Hu, Mou, Smith, K.C., Mouftah, H.T., Low power 2-of-3-valued CMOS self-checking circuits, Proc. of 13th Int'l. Symposium on Multiple-Valued Logic, Kyoto, Japan, pp. 64-69, May 23-25, 1983.

3. Kwong, R.H. Chang, T.N., Development of control system hardware demonstration for third generation spacecraft, Final Report, DOC Contract, OST 83-00042, pp. 178, Nov. 1984.

4. Lee, S.K., Buxton, W., Smith, K.C., A multi-touch three dimensional touch-sensitive tablet, to appear in Proc. of CHI'85, Conference on Human Factors in Computing Systems, San Francisco, April 1985, 8 mpp. (also to appear (upon request) at Graphics Interface '85 Conference, Montreal, May 27-31, 1985).

5. Levy-Mandel, A., Venetsanopoulos, A.N., Tsotsos J., Knowledge-based image processing application to the landmarking of cephalograms, Proceedings of the Tenth Symposium on Signal Processing and Applications, Nice France. May 20-24, 1985, submitted on October 25, 1984.

6. Mehta, N., Smith, K.C., Holmes, F.E., Featured extraction as a tool for computer input, Proc. Int'l. Conference on Acoustics, Speech and Signal Processing, Paris, France, May 3-5, 1982.

7. Mehta, N., Holmes, F.E., Smith, K.C., A fast image processor, Int'l. Electrical, Electronics Conference and Exposition, October 5-7, 1981.

8. Venetsanopoulos, A.N., Cappellini, V., Real-time image processing, a chapter in the book: Progress in Multidimensional Systems Theory. Tzafestas, S.G., Dekkare, Marcel (eds.), pp. 85, 1985, (in press).

9. West-Vukovich, G., Davison, E.J., Hughes, P.C., Decentralized control of large flexible space structures, IEEE Trans. of Automatic Control, Vol. AC-29, No.10, pp. 866-879, 1984.

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I) Summary

Robotics-related research in Industrial Engineering at the University of Toronto proceeds internally on an individual basis. Work directly related to flexible manufacturing and robotics has been on-going since about 1980.

The principal individuals whose work includes aspects associated with robotics research, are:

Dr. E.E. Pickett	Professor	sensors, image processing
Dr. A. Vannelli	Assist. Professor	flexible systems

Amongst the students currently supervised are 2 Ph.D. and 3 M.A.Sc. students working in the general areas of interest.

Areas of interest include computer vision, image processing, task planning, machine perception, robot sensors, monitoring and control of automated production, and flexible manufacturing systems.

Areas of specialization include automated inspection, image processing, scheduling, and graph partioning.

Individual interactions exist with the Robotics and Automation Laboratory in Mechanical Engineering and with NRC, Division of Electrical Engineering.

Funding sources include NSERC, through operating grants.

II) Bibliography

Publications related to robotics research include 4 refereed papers and 3 papers submitted. A sample of these is provided below:

1. Jha, R., Pickett, E.E., Object acquisition in the presence of uncertainties, Proc. ASME Conference on Computers in Engineering, Boston, MA, 1985.

2. Kusiak, A., Vannelli, A., Grouping problems in scheduling flexible manufacturing systems, invited submission to Robotica, 1984.

3. Pickett, E.E., Jha, R., Task planning and verification using visual feedback, Proc. SPIE, Intelligent Robots and Computer Vision, Vol 521, Cambridge, MA, 1984.

4. Vannelli, A., Kumar, K.R., A method for finding bottleneck cells for grouping part-machine families, to appear, International Journal of Production Research, 1985.

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I). Site Data

History and growth:

The AI Laboratory is a research group within the Department of Computer Science (DCS), and all its faculty members are members of the Computer Systems Research Institute (CSRI). DCS is responsible for academic appointments, the undergraduate and graduate programs, while CSRI is an inter-disciplinary body that administers hardware, technical personnel and facilitates the application for, and administration, of research grants. Thus, there are no directors, and administration is accomplished in a cooperative fashion. There is, however, a policy committee for the computing resources, comprised of faculty from both DCS and CSRI who are not all AI faculty, that deals with major policy questions. It is important to note that no formal entity within the university has been created for this effort.

The Computer Vision effort began in the early days of the laboratory, yet was consolidated only recently (1981). The early work is represented by Ph.D. theses by Normal Badler and Dick Peacocke. Since then, acquisitions of all hardware listed below occurred, and an inter-disciplinary emphasis has emerged. This led to strong relationships with the Departments of Psychology, Physiology, Mechanical Engineering and Electrical Engineering. A technical Report series titled "Research in Biological and Computational Vision" was born in 1984 out of this cooperation, and current titles are included below. It should be emphasized that the research efforts of this laboratory have only a minimal relationship to Robotics R & D, per se. Only in the broader context of intelligent robotics, where decision-making capabilities, planning, cognitive evaluation of perceptions, etc. are required, is this work of interest to researchers in robotics and automation. Also, this laboratory is not open to usage by others unless a direct research participation is anticipated.

In 1984, three faculty members were appointed as Fellows of the Canadian Institute for Advanced Research: John Mylopoulos, Hector Levesque and John Tsotsos. Raymond Reiter is also a Fellow, whose appointment was initially

with the University of British Columbia. Reiter will be joining the faculty in Toronto in May 1985. John Mylopoulos is the Nodal Coordinator for the University of Toronto effort of the CIAR's AI and Robotics Program.

Facilities:

Location: Sandford Fleming Building, Room 3204

- one DEC VAX 11/780 with:
  - 6 Mbytes memory
  - 2 450 Mbyte disks
  - one tape drive
  - 32 ports
  - two UNIBUSes

- 3 CDA Deltapro vision workstations each with:
  - 2 Mbytes memory
  - 5 Megaflop array processor
  - colour graphics display processor (512 × 512 × 16)
  - keyboard
  - trackball
  - 13" colour Hitachi monitor

- RCA Ultracon camera and lenses, Sanyo camera

- MATROX frame grabber, memory and B/W display (256 × 256 × 8)

- CONRAC 25" colour monitor (512 × 512)

- 8 Symbolics 3640 Lisp processors (on order) each with
  - 4 Mbytes memory
  - (2 processors with tape cartridge)

- 1 IMAGEN Laser printer (on order)

- 1 SUN-2/50-2 desktop workstation (on order)

In addition, there are numerous terminals. A local area network facilitates communication among various processors as well as connects the AI facilities to the rest of the University's computing environment. DCS is a node for the CSNET communications network, connecting departments of computer science throughout North America.

Affiliations:

Our laboratory is a node of the Canadian Institute for Advanced Research's program on Artificial Intelligence and Robotics. Each AI faculty member is also a member of the University's Computer Systems Research Institute.

Source(s) and amount of funding:

NOTE: NSERC Individual Operating Grants have not been included. Their total varies, and increases annually, and currently totals approximately $100,000 annually.

Abbreviations Used:

NSERC - Natural Sciences and Engineering Research Council
OHF - Ontario Heart Foundation
DSS - Department of Supply and Services
BILD - Ontario Business and Industrial Leadership Development Program
DEC - Digital Equipment Corporation, Maynard, MA
CDA - Computer Design and Applications, Waltham, MA
DC - Department of Communications, Ottawa

Source	Years	Amount	Comments
OHF	81-82	19,600	Computer Analysis of Cardiac Imagery for Left Ventricular Performance Evaluation
OHF	82-83	25,225	
DSS	82-83	30,907	Knowledge-Based Interpretation Systems and Knowledge Representation Formalisms (administered by Defence Research Establishment Atlantic)
DSS	83-84	32,623	
NSERC	83-84	32,000	Laboratory for Computational Medicine Infrastructure Grant
Connaught	82-84	21,400	Expert Systems with Applications to Visual Motion Analysis and Medical Diagnosis
BILD	82-83	180,000	Equipment Grant (for VAX 11/780)
BILD	83-84	115,000	Equipment Grant (for CDA Deltapros)
Connaught	84-85	24,000	Semantic Interpretation and Disambiguation
DC	84-85	50,000	Implementation of Representation and Control Structures
CDA	83-84	70,000	Equipment Grant (for CDA Deltapros)

Source	Years	Amount	Comments
DEC	82-83	180,000	Equipment Grant (for VAX 11/780)
NSERC	83-86	300,000	Strategic Grant (TAXIS Implementation)
NSERC	84-87	995,000	Strategic Grant - 2nd Generation Expert Systems
NSERC	84-85	500,000	Equipment Grant - Lisp Machines

Fee structure for external services:

The facilities are managed by CSRI, and the fee structure can be obtained from that source (David Galloway is the CSRI Laboratory Manager). As mentioned previously, only users who are research collaborators are permitted access to the AI facilities.

Clientele (Industrial and Government Contacts):

1) Digital Equipment Corporation, Maynard, MA. Research partnership (resulted in grant of $180,000 used in purchase of VAX 11/780 and associated equipment).
2) Computer Design and Applications, Waltham, MA. Research partnership (resulted in grant of $70,000 used in purchase of CDA Deltapros).
3) Defense Research Establishment Atlantic, Dartmount NS (Dept. of Supply and Services) Research Contract for studies of knowledge representation and control schemes.
4) Canadian Artificial Intelligence Products Corp., Nepean, Ont.
5) Spar Aerospace, Toronto, Ont.
6) Bell-Northern Research, Ottawa, Ont.
7) Dept. of Communications, Ottawa. Research contract to develop knowledge representation systems and control structures.

Plans for expansion:

The AI Lab is seeking to hire two Research Scientists (Ph.D. level with AI experience), and two programmers (M.Sc. level, with AI experience). Additional faculty appointments are being considered. With respect to hardware plans, the only proposed acquisitions are for personal workstations (like SUN's) for each faculty member.

II) Personnel Data

Faculty:

G. Hirst	computational linguistic cognitive science
A.D. Jepson	applied mathematics computer vision

H.J. Levesque	Knowledge Representation Knowledge-Based Systems
J. Mylopoulos	Knowledge Representation Knowledge-Based Systems Applications of AI to Information Systems
R. Reiter	Knowledge Representation Applications of AI to Databases
J.K. Tsotsos	Computer Vision Knowledge-Based Systems Applications of AI to Medicine

Associated Faculty:

A. Goldenberg	Mech. Eng.	Robotics and Automation
P. Hallett	Physiology	Visual Neurophysiology
P. Kolers	Psychology	Motion Perception
H. Kwan	Physiology	Visuo-Motor Neurophysiology
A. Venetsanopoulos	Elect. Eng.	Digital Image Processing

Visiting Faculty (1985):

A. Dempster	Harvard	Probabilistic Schemes for Evidential Reasoning
M. Fox	CMU	Intelligent Systems for Flexible Manufacturing

Staff:

Fleet	Research Associate	Early Visual Processes
Kramer	Research Scientist	Knowledge Representation
Meghini	Research Scientist	AI Applications to Information Systems
Nunes	Programmer	Knowledge-Based Systems
Shibahara	Research Scientist	Knowledge-Based Systems

Graduate Students:

In the field of computer vision, there are presently six Ph.D. students and two M.Sc. students.

III) Research Activities

Research areas:

There are four primary research areas, and several other sub-interests within them. These are:

Knowledge Representation:
- Logical Foundations
- Non-Monotonic Logic
- Applications to Databases and Software Engineering

Knowledge-Based Systems:
- Evidential Reasoning
- Casual and Temporal Reasoning
- Control Structures

Computational Linguistics:
- Cognitive Science
- Natural Language Understanding

Computer Vision:
- Motion Perception
- Cooperative Computation
- Human Visual Perception
- Attentive Visual Processes

Principal research objectives and/or directions:

Within the sub-areas of AI listed above, the Laboratory's prime objective is basic research as opposed to applications work or development. Some applications systems have been developed as well, however, primarily in medical domains. Within Computer Vision, the development of computational theories that lead to a deeper understanding of the nature of human perception and its interaction with other human cognitive processes is of key interest. The group believes that such a deeper understanding is necessary for the development of truly useful and intelligent machine vision systems.

Major software programs:

A large variety of image manipulation software has been defined for usage with the MATROX frame buffer system, the IKONAS graphics system (hardware that is part of the CSRI facility), and the CDA workstations. This software resides in the RASTERSOFT package that is available for external usage. In addition, a large package of software is in the final stage of development that allows the CDA workstation to run full C programs on its array processor, as well as manipulate colour images, and do animation.

Other major software programs include the ALVEN visual motion expert system for human left ventricular dynamics evaluation, stereo-tracking programs, and spatio-temporal filter implementations.

Parties with whom the AI Laboratory communicates:

The Computer Vision group has close collaborative ties with the Computer Vision and Robotics Laboratory of McGill University, in addition to the associated faculty listed earlier.

Position in robotics R & D community:

As mentioned previously, the group's research is not directly related to Robotics research, except in the broad context of intelligent behaviour by machine. It is clear that Robotics research must eventually consider results from other areas of AI that currently seem not to be relevant. The laboratory is open for visits by interested persons (on appointment) and requests for technical reports or papers are welcome.

IV) Bibliography:

This bibliography includes only those papers that have relevance to Computer Vision, and is not a complete listing of all publications of the AI Laboratory.

Journal Papers and Book Chapters:

1. Fleet, D.J., Hallett, P.E., Jepson, A.D., Spatio temporal inseparability in early visual processing, Biological Cybernetics, (submitted).

2. Gershon, R., Aspects of perception and computation in colour vision, Computer Vision, Graphics and Image Processing, (to appear).

3. Jenkin, M., Tsotsos, J.K., Applying temporal constraints to the dynamic stereo problem, Computer Vision, Graphics and Image Processing, (to appear).

4. Jenkin, M., Tracking three-dimensional moving light displays, in: Motion: Representation and Perception, Badler and Tsotsos (eds.), ACM Publications, (in press) 1985.

5. Tsotsos, J.K., A relaxation process for the temporal integration of time-varying matching evidence, IEEE Pattern Analysis and Machine Intelligence, (submitted).

6. Tsotsos, J.K., The scope of research on motion: sensational, perception, representation and generation, in: Motion: Representation and Perception, Badler and Tsotsos (eds.), ACM Publications, (in press), 1985.

7. Tsotsos, J.K., Representational axes and temporal cooperative processes, in: Vision, Brain and Cooperative Computation, Arbib and Hanson (eds.), (in press), MIT Press/Bradford Books, 1985.

8. Tsotsos, J.K., Covvey, H.D., Mylopoulos, J., McLaughlin, P., The role of symbolic processing in the computer evaluation of left ventricular wall motion: the ALVEN system, in: Ventricular Wall Motion, U. Sigwart and P. Heintzen (eds.), Georg Thieme Verlag, 1984.

9. Tsotsos, J.K., The computer assessment of left ventricular wall motion: the ALVEN Expert System, Computers and BioMedical Research, (to appear).

10. Tsotsos, J.K., "The role of knowledge organization in representation and interpretation of time-varying data: the ALVEN system, Computational Intelligence, Feb. 1985.

11. Tsotsos, J.K., The scope of motion research: from image intensity changes to semantic abstractions, Computer Graphics, Vol. 18, No. 1, p. 7-11, Jan. 1984.

12. Tsotsos, J.K., Knowledge and the visual process: content, form and use, Pattern Recognition, Special Issue on Knowledge-Based Vision, Vol. 17, No. 1, p. 13-26, Jan. 1984.

13. Tsotsos, J., Mylopoulos, J., Covvey, H.D., Zucker, S.W., A framework for visual motion understanding, IEEE Pattern Analysis and Machine Intelligence, Special Issue on Computer Analysis of Time-Varying Imagery, p. 563-573, Nov. 1980.

Papers in Refereed Conference Proceeding

1. Fleet, D.J., How good is the DOG as a model of retinal processing?, International Joint Conference on Artificial Intelligence - 85, (submitted).

2. Fleet, D.J., Jepson, A.D., On the detection of 2-d velocity, International Joint Conference on Artificial Intelligence - 85, (submitted).

3. Gershon, R., Empirical results with a model of color vision, Proc. IEEE Conf. Computer Vision and Pattern Recognition, San Francisco, CA. 1985.

4. Jenkin, M.R.M., Applying temporal constraints to the problem of stereopsis of time-varying imagery, Proc. Fifth National Conference, Canadian Society for Computational Studies of Intelligence, London, Ontario, 1984.

5. Jenkin, M.R.M., Tracking three-dimensional moving light displays, Proc. 1983 ACM SIGARTSIGGRAPH Workshop on Motion, Toronto, 1983.

6. Levy-Mandel, A.D., Tsotsos, J.K. Venetsanopoulos, A.N., Knowledge-based landmarking of cephalograms, Proceedings of the 1984 Symposium on Communications, June 1984, Kingston, Ontario.

7. Tsotsos, J.K., Jepson, A.D., Fleet, D.J., Motion understanding meets early vision: an introduction, IEEE Conference on Applications of Artificial Intelligence, Denver, pp. 239-244, Dec. 1984.

8. Tsotsos, J.K., Cooperative computation and time, IEEE Workshop on Computer Vision: Representation and Control, Annapolis, p, 231-237, May 1984.

9. Tsotsos, J.K., Knowledge of the visual process: content, form and use, Proc. International Conference on Pattern Recognition, Munich, p. 654-669, Oct. 1982.

10. Tsotsos, J.K., Temporal event recognition: an application to left ventricular performance, Proc. International Joint Conference on Artificial Intelligence, Vancouver, B.C., p. 900-907, Aug. 1981.

11. Tsotsos, J.K., On classifying time-varying events, Proceedings on Pattern Recognition and Image Processing, Dallas, p. 193-199, Aug. 1981.

12. Tsotsos, J., Mylopoulos, J., Covvey, H.D., Zucker, S.W., ALVEN: a study on motion understanding by computer, Proc. International Joint Conference on Artificial Intelligence, Tokyo, p. 890-892, Aug. 1979.

13. Tsotsos, J., Knowledge-base driven analysis of cinecardioangiograms, Proc. Fifth International Joint Conference on Artificial Intelligence, MIT, Cambridge, Mass., p. 699, Aug. 1977.

14. Tsotsos, J., Some notes on motion understanding, Proc. Fifth International Joint Conference on Artificial Intelligence, MIT, Cambridge, Mass., p. 611. Aug. 1977.

Books Edited:

1. Badler, N.I., Tsotsos, J.K., Motion: Representation and Perception, ACM Publications, (in press), 1985.

2. Tsotsos, J.K., Machine Understanding of Visual Motion, for the Robotics Series, T. Kanade (ed.), Kluwer Academic Publishers, Deventer, The Netherlands, (in preparation).

Computer Science Technical Reports:

Departmental Technical Reports

Abbreviations:

LCM - Laboratory for Computational Medicine
RBCV - Research in Biological and Computational Vision
CSRG - Computer Systems Research Group

1. Barron, J., A survey of approaches for determining optic flow, environmental layout and egomotion, RBCV-TR-85-5, March, 1985.

2. Fleet, D.J., The early processing of spatio-temporal visual information, RBCV-TR-84-7, March 1985.

3. Fleet, D.J., Jepson, A.D., A cascaded filter approach to the construction of velocity selective mechanisms, RBCV-TR-84-6, March 1985.

4. Fleet, D.J., Jepson, A.D., Hallett, P.E., A spatio-temporal model for early visual processing, RBCV-TR-84-1, May 1984.

5. Gerhson, R., Survey on color -- Aspects of perception and computation, RBCV-TR-84-4, 1984.

6. Jenkin, M.R.M., The stereopsis of time-varying imagery, RCBV-TR-84-3, 1984.

7. Tsotsos, J.K., Bylopoulos, J., Shibahara, T., Research on knowledge-based systems: PSN, ALVEN, and CAA, LCM-TR84-1, May, 1984.

8. Tsotsos, J.K., A framework for visual motion understanding, CSRG TR-114, 1980.

9. Tsotsos, J., A prototype motion understanding system, TR-93, 1976.

10. Tsotsos, J., Representational axes and temporal cooperative processes, RBCV-TR84-2, May 1984.

Theses:

1. Air, J., The Grouping of Primitive Visual Tokens (M.Sc. 1985).

2. Down, B., Using Feedback in Motion Understanding (M.Sc. 1983).

3. Fleet, D., The Early Processing of Spatio-Temporal Visual Information (M.Sc. 1984).

4. Jenkin, M., The Stereopsis of Time-Varying Imagery (M.Sc. 1984).

5. Levy-Mandel, A., Knowledge-Based Landmarking of Cephalograms (M.Sc. 1984).

6. Lobo, N., Directionally-Selective, Volocity-Sensitive Motion Detection (M.Sc. 1985).

7. Tsotsos, J.K., A Prototype Motion Understanding System (M.Sc. 1976).

Theses in Progress:

1. Barron, J., Computing Egomotion and Environmental Layout Time-Varying Errorful Image Volocities (Ph.D. Jan. 1980 - present).

2. Buchanan, C., Attentive Vision Models and their Interaction with Early Processes (M.Sc. Sept. 84 - present).

3. Dudek, G., Analysis of Spatio-Temporal Cooperative Computation (Ph.D. Jan. 1984 - present).

4. Gershon, R., Colour Perception and Computation (Ph.D. Sept. 1982 - present).

5. Jenkin, M., Visual Stereoscopic Computation (Ph.D. Sept. 1983 - present).

6. Lobo, N., Early Cooperative Processes in Vision (Ph.D. Sept. 1984 - present).

7. Marcus, H., Texture Perception (Ph.D. Sept. 1982 - present).

8. Stanley, D., Expert Vision Systems for Remote-Sensing Applications (M.Sc. Sept. 84 - present).

WATERLOO, UNIVERSITY OF

Department of Systems Design Engineering

Pattern Analysis and Machine Intelligence Group

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I) Site Data

History and growth:

The PAMI Lab was established in 1980 with the objective of providing space and facilities to researchers in the areas of pattern analysis and machine intelligence. In the following two years, it was awarded an NSERC Major Equipment Grant and an NSERC Equipment Grant to acquire an image processing and display system as well as a VAX 11/750. Later, with the support of research contracts and a BILD Grant, more computing and computer graphic facilities were acquired. Since then, the research activities of the Group have continued to grow. In 1981, PAMI, along with five other research groups, became involved in the planning and organization of the Institute of Computer Research (University of Waterloo). All these years, PAMI has been very active and successful in promoting the Institute's activities and the transferral of high technology to the industrial sector.

Facilities:

Current research facilities of the PAMI Group include: a) several robots (including a vision-based roving robot with a flexible arm in the development stage); b) a VAX 11/780, a VAX 11/750, an IBM 4342, several MICRO VAX and an IBM PC/XT computers; c) a Grinnell Image Display System; d) an EIKONIX High Resolution Image Scanning System; e) several video digitizers; f) a Matrix Colour Graphic Recorder; g) an FPS-100E System; h) various graphic stations.

Source(s) and amount of funding:

Funding sources include NSERC, through operating, strategic and infrastructure grants, as well as contracts from NCR and Taran Furs. Overall funding for research is at the annual level of $800K.

Plans for expansion:

In 1986, the PAMI Laboratory, and all its acquired facilities, will be moved to the William Davis Building of Computer Research which is now under

construction. Currently, the PAMI Group participates in the planning and the formation of another university-based center for computer integrated manufacturing known as WATCIM (Waterloo Computer Integrated Manufacturing). An important plan for the PAMI Group is to develop and transfer high technology to industry focussing in the pattern recognition and machine intelligence aspects of Fifth Generation Computing, image processing and robotics.

II) Personnel Data

Director:	A.K.C. Wong	pattern analysis, machine intelligence, computer vision, knowledge-based systems, robotics
Faculty:	M.E. Jernigan	pattern recognition, signal and image processing, computer vision
	M.S. Kamel	expert systems, robotic vision and task planning office information system, mathematical software
	H.C. Shen	texture analysis, knowledge-based systems, intelligent image information system, robotic language and control
	G. Savage	discrete models of field and continuum problems, computer-aided design
	K. Singhal	CAD design of non-linear and linear circuits and systems, computer methods for optimal product design, VLSI, simulations
	B. Wills	computer-aided instruction, computer and music, system simulations
ffiliated Faculty:	M. Vidyasagar	control theory, robot control

Additional lab personnel consist of a laboratory manager, two secretaries, a hardware engineer, a software engineer and 35 graduate students (15 Ph.D., 20 Masters).

III) Research Activities

Research areas:

Areas of research include pattern recognition (Wong, Jernigan), machine intelligence (Wong, Shen), knowledge-based systems (Wong, Kamel, Shen), computer-aided design (Savage, Singhal, Wills), image processing (Jernigan,

Shen), robot vision and control (Wong, Jernigan, Kamel, Shen, Vidyasager) and flexible manufacturing (shared).

Research objectives:

The principal objective of PAMI is to advance the state-of-the-art in pattern recognition and artificial intelligence with a focus on Fifth Generation computing, knowledge-based systems and robotics. As well, an objective is to develop human resources for high technology research and development particularly in the area of machine intelligence and robotics. A final objective is to promote technology transfer between the universities and industry.

Areas of specialisation:

The areas of specialization of the PAMI group are pattern recognition, artificial intelligence, computer vision, knowledge-based systems, computer-aided design and robotic control systems.

Major accomplishments to date:

The level of accomplishment may best be summarized by the following statistics: (since 1981 in robotics-related topics) over 30 refereed publications, nearly $1 million in industrial contracts, and a $1M 3-year strategic grant for robotic vision and control.

Major software programs developed or used:

Major software programs developed and extensively used include: a) pattern recognition package; b) a pattern-analysis package on discrete-valued and mixed-mode data; c) an image processing package; d) a graph morphism package; e) random graph synthesis algorithm; f) path and trajectory planning for roving robots; g) 3-D object recognition and synthesis algorithms; h) interactive robotic control package; i) integrated knowledge based systems package; j) office automation simulation package and k) computer graphic package.

Parties with whom the PAMI Group communicates:

Close relationships exist with the following organizations: a) Ontario Robotic Center, b) NRC Ottawa, c) Electrical Engineering Department, Hull University, d) The Robotic Institute, Carnegie Mellon University, e) NRC Canada Ltd., f) Taran Furs (Montreal) Ltd., g) General Motor, i) Digital Equipment Corporation, j) IBM Corporation and k) Bell Northern Research.

V) Bibliography

Publications related to robotics research include more than 30 refereed papers, 10 other publications and 5 papers submitted. A sample of these is provided below:

1. Jernigan, M.E., Wardell, R.W., Does the eye contain optimal edge detection mechanisms?, IEEE Trans. Sys. Man and Cyb., Vol. SMC-11. No. 6, 441-444, 1981.

2. Jernigan, M.E., D'Astous, F., Entropy based texture analysis in the spatial frequency domain, IEEE 1980 Conference on Cybernetics and Society, 1980.

3. Kamel, M.S., Knowledge acquisition using pattern recognition techniques, Proc. of Conference on Intelligent Systems and Machines, Rochester, 1984.

4. Shen, H.C., Wong, A.K.C., Generalized texture representation and Metric, Computer Vision, Graphics, and Image Processing 23, 1983, pp. 187-206.

5. Signarowski, G.F.P., Shen, H.C., Development of an interface between a robot programming system and its environment, Proc. of International Conf. on Cybernetics and Society, Halifax, 1984.

6. Vannelli, A., Vidyasagar, M., Maximal Lyapunov functions and domains of attraction for autonomous nonlinear systems, to appear in Automatica, p. 34, accepted April 4, 1983.

7. Wong, A.K.C., You, M.L., Entropy and distance of random graphs with application to structural pattern recognition, to appear in IEEE Trans. on Pattern Analysis and Machine Intellgence, 1985.

8. Wong, A.K.C., Lu, S.W., Representation of 3-D objects by attributed hypergraphs for computer vision system, Proc. of 1983 International Conference on Systems, Man and Cybernetics, pp. 49-53, 1983.

9. Wong, A.K.C., Grahraman, D.E., Random graphs: structural-contextural dichotomy, IEEE Trans. on Pattern Analysis and Machine Intelligence, Vol. PAMI-2, No. 4, pp. 341-348, 1980.

WESTERN ONTARIO, UNIVERSITY OF

Faculty of Engineering Science

Robotics Laboratory

London, Ontario
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Professor J.A. MacDonald
(519) 679-3894

I) Summary

Robotics research began in 1981 under the direction of Professor MacDonald with four students. A pick-and-place robot with optic sensing capability was designed and constructed for the robotics laboratory. The design task included the development of software, interfacing, kinematic analysis and safety features as well.

The equipment in the robotics laboratory includes: a Dec-10 computer, personal computers, access to a Cyber and Prime 500 computers, and the previously mentioned pick-and-place robot ("Xylvia"). Different robotic devices are under construction in the robotics laboratory.

Dr. MacDonald's interest is in the area of robotic interfaces. His work covers sensor development, kinematic modelling, pattern recognition and prosthesis. There is also interest in feed-back control and pattern recognition. Most of the work performed is directed towards material handling problems, transfer of parts, and assembly operations. A number of graduate students are engaged in robotics research work.

II) Bibliography

1. MacDonald, J.A., A microprocessor controlled robotic arm manipulator, Proceedings of the Ninth Canadian Congress of Applied Mechanics, University of Saskatchewan, Saskatoon, 1983.

2. MacDonald, J.A., XYLVIA - A Pick and Place Robot, CAD/CAM and Robotics, October, 1983.

CONCORDIA UNIVERSITY

Department of Mechanical Engineering

Centre for Industrial Control

SGW Campus - Annex B
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Professor R.M.H. Cheng
(514) 879-4552

I) Site Data

Centre's history and growth:

Formerly FLUID CONTROL CENTRE - a centre of excellence created with the funding provided by an NRC Development Grant in 1973 - the Centre for Industrial Control (established in 1983) provides the facilities for research and development in control and automation for faculty members and graduate students of the Mechanical Engineering Department of Concordia University. It is also dedicated to technology transfer to the local industry.

Facilities:

robots: Unimation PUMA 560, Rhino XR-2, Armdroid, in-house developed pneumatic robot, automatic guided vehicle (AGV) (under development)

computers: DEC PDP-11, Sage IV (16 bit micro), Northstar Horizon (8 bit micro), Northstar Advantage (8/16 bit micro), Rainbow 100 (16 bit micro), IBM-PC, Intel System 310, VAX 780 (plus Norpak graphics system), CDC system 820/830 (university mainframe)

Source(s) and amount of funding: (for 1984-85 only)

NSERC Personal Research Operating Grants	$209,696
NSERC Strategic Grant (Stepanenko and T.S. Sankar)	$ 57,100
NSERC Infrastructure Grant (Cheng, S. Sankar, etc.)	$ 45,000
FCAC Grant to the Centre (Kwok, Cheng, etc.)	$ 20,000
NSERC Equipment Grant (Krepec, Cheng)	$ 43,600
NSERC PRAI Grants (Svoboda, etc.)	$193,500
TOTAL (for 1984-85 only)	$568,896

Clientele:

Department of Supplies and Services
Transport Canada
Other funding agencies
Private industries

II) Personnel Data

Principal Personnel:

Dr. R.M.H. Cheng	Professor and Director, CIC	industrial automation
Dr. C.K. Kwok	Professor	fluid control
Dr. T. Krepec	Associate Professor	fuel control
Dr. T.S. Sankar	Professor and Chairman, Mechanical Engineering Department	mechanical vibrations, robotics
Dr. Y. Stepanenko	Professor	robotics
Dr. J. Svoboda	Associate Professor	flight simulator

Associated Personnel:

Y. Courbet	Research Assistant	camera vision, automatic guided vehicle
Dr. M.A. Daoud	Research Associate	robotics
Dr. A.E.F. Fahim	Adjunct Assistant Professor	control systems
H. Hong	Research Assistant	robotics
N. Krouglicoff	Research Associate	electronics, online vision monitor and control
Dr. S. LeQuoc	Adjunct Associate Professor	robotics, electrohydraulics
D.K.H. Leung	Research Assistant	electrohydraulics
T. Montor	Research Assistant	robotic synchronization control
R. Rajagopalan	Research Assistant	robotics
M. Surpaceanu	Research Associate	mechanical engineering

III) Research Activities

Research areas (examples of major areas):

- Automatic Guided Vehicle - Very likely the first and only research group in Canada involved in research and development of medium-duty AGV (150 kg payload), equipped with low-cost camera vision and on-line digital control.
- Synchronization control of industrial robot with a conveyor system - With a low-cost camera feature, the system detects the orientation and changing position of an object as it comes down the conveyor. Synchronization control ensures that robotic manipulator moves in to pick up (or otherwise process) the object.
- Dynamic Simulation of Robotic Manipulators using Systems Approach.

Principal research objectives and/or directions:

To develop low-cost high-technology systems and techniques to improve productivity (manufacturing).

Major accomplishments/developments to date:

The CIC, in its present dedication to research and development in robotics and related areas, has acquired considerable recognition in the local industries. The acquisition of an UNIMATION PUMA 560 robot and accessories, plus the donation by INTEL CORP of a system 310 computer and peripherals has greatly strengthened the Centre's capability to deal with relevant robotic research areas.

Major software programs either developed or used:

- Linear scanning camera to S100 bus interface software
- Micro-eye camera to Northstar Advantage operating software
- Software for the orientation determination of a class of objects using 2-D binary images
- Mathematical model analysis and control program of Rhino robot
- Interactive simulations of robotic manipulators with graphic features (implemented on VAX 780)

Parties with whom CIC communicates:

- L'ecole de Technologie Superieure, Montreal, P.Q.
- DSL-Dynamic Sciences Ltd., St. Laurent, P.Q.
- CAE Electronics, St. Laurent, P.Q.
- University of Ottawa, Ottawa, Ont.

Position in robotics R & D community:

The Centre wishes to address itself to high technology applications using relatively low-cost equipment and simple algorithms. It complements the work of organizations which attempt to help the small and medium industries to improve productivity and quality.

Participation in the Joint Coordinating Forum on International Cooperation in Advanced Robotics:

The Centre is willing to participate in either overall planning of robotic research, or in carrying out specific tasks or research areas. The projects that will be of greatest interest at the present should address automatic guided vehicle research (with camera vision capabilities) and synchronization control of robotics (plus conveyor systems) and static and dynamic calibration of industrial robots under different loading conditions. Another area of interest is in underwater robotics.

IV) Bibliography

1. Cheng, R.M.H., Harris, O.G., A power bond graphs approach for modelling pneumatic control systems, Journal of Fluid Control, accepted for publication, 1985.

2. Cheng, R.M.H., LeQuoc, S., Athanasoulias, D., On-line system for locating the position of the centroid of a flat object, Ninth Canadian Congress for Applied Mechanics, 1982.

3. Fahim, A.E.F., Cheng, R.M.H, On line system for identifying the angular orientation of a class of engineering components, Transactions of IEEE, Industrial Electronics and Control Instrumentation, Vol. IECI-17, No. 3, 1980.

4. Fahim, A.E.F., Sankar, S., Cheng, R.M.H., Computer-aid optimal design of a polar-based, NC contouring system: synthesis and contouring error minimization, ASME Winter Annual Meeting, Boston, Paper No.83-DET-62, 1983.

5. Lee, R.S., R.M.H. Cheng, Table positioning by a dual purpose probe, Proceedings of 4th International Conference on Assembly Automations, Tokyo, 1983.

6. LeQuoc, S., Cheng, R.M.H., Kelly, M., A high level computer-aided language for the design and simulation of logic control systems, Computer in Engineering, Vol. 4, pp. 27-32, ASME 1982.

7. LeQuoc, S., Cheng, R.M.H., Limaye, A., A new tuneable electrohydraulic servovalve configuration to achieve high velocity, fast response and high damping, ASME '84 Winter Annual Meeting, Paper No. 84-WA/DSC-11.

8. Mongeon, M., Design and development of a microprocessor control for a blood testing machine, Report No. CIC-0001, September 1984.

9. Stephanenko, Y., Sankar, T.S., On dynamic simulation of robotic manipulators, Proceedings of the 1984 ASME International Computer in Engineering Conference and Exhibit, Las Vegas, Nevada, August 1984.

10. Stepanenko, Y., Sankar, T.S., On the accuracy of force-reflecting of master-slave manipulators for hazardous environment, Proceedings of the 1984 Annual CSME Conference, Halifax, Nova Scotia, May 1984.

11. Stepanenko, Y., Sankar, T.S., Position and force-reflecting accuracy of remote manipulators, Transactions CSME, accepted for publication.

12. Stepanenko, Y., Sankar, T.S., Limit cycles in compliant actuators due to clearances in kinematic chains, Proceedings of the 1984 ASM Winter Annual Meeting, New Orleans, Louisiana, December 9-14, 1984. (Available in ASME publication no. G00275).

Technical Reports:

1. Athanasoulias, C., Cheng R.M.H., LeQuoc, S., User Manual for the Circuit Simulation Program (CSP), Report No. CIC-0006, September 1984.

2. Courbet, Y., Camera/Microcomputer Interface for Automatic Guided Vehicles, Report No. CIC-0007, September 1984.

3. Leung, D.K.H., Simulation and Analysis of a New Tunable Electro-Hydraulic Servovalve Configuration by Small Perturbation Method, Report No. CIC-0005, September 1984.

4. Limaye, A., Hydraulic Servovalve Configuration, Report No. CIC-0003, September 1984.

5. Montor, T., Robotic Assembly with Camera Vision, Report No. CIC-0004, September 1984.

6. Surpaceanu, M., Design of an Automatic Guided Vehicle, Report No. CIC-0002, September 1984.

ÉCOLE POLYTECHNIQUE

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Department of Mechanical Engineering

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Professor R. Baldur
(514) 340-4861

I) Summary

Robotics research within the department first began late in 1982. Professors R. Baldur and A. Bazergui are the principal researchers with eight graduate students who also conduct robotics research. Facilities include two in-house developed robots and several types of computers.

Research objectives are: to reduce the cost of robots, to simplify control techniques, to develop grippers capable of grasping delicate objects, and to address self-contained, automatic vehicles. To this end, research areas include: computer-controlled pneumatic manipulators, inflatable manipulators, pneumatic, force-sensing grippers, and control of hydraulic actuators.

II) Bibliography

1. Baldur, R., An inexpensive robot for mechanical engineering students, Robots 8 Conference - Detroit, June 1984.

2. Baldur, R., Design of an experimental automatically guided vehicle, CAD/CAM and Robotics Conference, Toronto, June 1984.

3. Baldur, R., Trajectory optimization of a guided vehicle, EAM Symposium, June 1984.

4. Baldur, R., Hydraulic control of pneumatic actuators, CAD/CAM Robots Conference, Toronto. June 1984.

ÉCOLE POLYTECHNIQUE

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Department of Electrical Engineering

Le Laboratoire de Robotique

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Professor R.M. Desantis
(514) 340 4552

I) Summary

Personnel associated with the robotics lab have been conducting robotics-related research for approximately six years. Initially this research was of a theoretical nature and addressed such topics as decentralized control, hierarchial systems and optimisation. With the establishment of the lab, activities are gradually shifting towards those of a technical, experimental nature. These topics include: modeling, dynamic and graphic simulation of robots, vision control of robots, actuator design, and control algorithm development.

Research facilities available through the lab include: 2 Rhino XR-1 robots, a Matrox Vision System, several microcomputers, actuators, and programmable controllers. In addition, a PDP 11/60, a VAX 11/750 and several graphics terminals are available via the CAD laboratory. Funding for the equipment was provided by the Ministère de l'Education du Québec, The Natural Sciences and Engineering Research Council of Canada, and by le Direction de la recherche de l'École Polytechnique. Expansion plans call for acquisition of an industrial robot and an IBM-AT computer.

Research projects being performed at this time by graduate students (4 MASc, 2 Ph.D.) and professors involve image analysis, graphic simulation of robots, robot control through vision and trajectory optimisation, robot programming languages and databases, hardware for real-time simulation, and the application of AI to flexible automation.

Groups with whom the lab collaborates include: l'Institut de recherche de l'Hydro-Québec, the Industrial Materials Research Institute of the National Research Council of Canada, Northern Telecom, le Centre de Recherche Industrielle du Québec, le Laboratoire de Robotique et d'Automatisation de l'Universita du Québec à Chicoutimi, and le Laboratoire d'Automatique et d'Analyse des Systemes de Toulouse.

II) Bibliography

None at this time.

McGILL UNIVERSITY

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I) Site Data

History and growth:

As the DATAC Computer Laboratory, this group has been working in computer aided mechanical automation since 1969. Coordinated research in robotics was started in September 1984. This is integrated with the McGill Centre for Robotics (official name to be decided).

Facilities:

GMF/S1 5-axis computer controlled industrial robot, ORCAtech 3000 graphics computer and workstation for CAD, other CAD hardware including micros and graphics peripherals, EMCO 3-axis miniature CNC milling machine, CGE-Honeywell HS4020 industrial scale process automation computer.

Sources and amount of funding (current year):

Department equipment grant: $84k, NSERC personal operating grants: $74k, Canadian Ministry of State Grant to Establish a Robotics Research Centre at McGill: $700k, FCAC (Quebec): $54k (applied for), "Action Structurantes (Quebec): $1500k (applied for).

Fee structure for external services:

A detailed fee schedule will be formulated. Currently, engineering consultation services in automation, design and analysis are provided at $100/h (maximum, per principal).

II) Personnel Data

Principal Personnel:

J. Angeles	Assoc. Professor	kinematics and dynamics
A. Misra	Assoc. Professor	vibrations
M.P. Paidoussis	Professor & Dept. Chrmn.	system dynamics
L.J. Vroomen	Faculty Lecturer	instrumentation
P.J. Zsombor-Murray	Assoc. Professor	computer control

Associated Personnel:

K. Anderson	Research Fellow	robot modelling and control
P. Baracos	Research Fellow	automata and control
R. Bubic	Research Engineer	actuators
B. Chen	Research Fellow	manipulator design
X. Cyril	Research Assistant	automata and control
R. Hudson	Research Fellow	robot modelling and control
M. Maschtall	Research Assistant	biomedical sensing
H. Qi	Research Fellow	manipulator sensor
K. Spring	Research Assistant	robot modelling and control
X. Wang	Research Fellow	automatic control
M. Zacharia	Research Assistant	dynamic simulation

III) Research Activities

Research areas:

Trajectory planning, computer control, kinematic and dynamic modelling and control, sensors and artificial muscle/actuators.

Principal research objectives and/or directions:

Enhancement of robot performance with optimized trajectory programming, novel robotic configurations, including multiple closed-loop manipulators, distributed control of robotic motion degrees-of-freedom.

Areas of specialization:

Continuous path operations, sensor based systems, binary-decision (BD) automata and other programmable controllers, robotic actuators.

Major accomplishments/developments to date:

Software for kinematic and dynamic modelling and trajectory planning, BD machine design, development and programming, variable reference matrix sensors; an artificial skeletal muscle, real-time shared data acquisition and control facility.

Major software programs developed or used:

Kinematics of 5 and 6-axis serial manipulators, dynamic modelling of n-link robot manipulators, dynamic modelling of mechanical systems comprising flexible links, kinematic control of robot manipulators in the presence of singularities and redundancies, software for pick-and-place operations, an optimizing BD program compiler.

Parties with whom McGill group communicates:

- Computer Vision and Robotics Laboratory, McGill University
- Biomedical Research Unit, McGill University
- School of Computer Science, McGill University
- The Microelectronics Centre, University of Manitoba

Position in robotics R & D community:

The group looks forward to collaboration with other robotics R&D centres and related Canadian industry. It believes that its contributions to manufacturing applications will be substantial, especially as regards control hardware and software (e.g., for tasks such as welding, palletizing and attendant sensory instrumentation).

Participation in the Joint Coordinating Forum on International Cooperation in Advanced Robotics:

Projects which the group would desire to become jointly involved in would be those which address:

- Systems for the automatic computation of position and orientation of objects
- Software for pick-and-place operations
- Software for continuous path operations
- Dynamic control of robotic manipulators and their design
- Mechanical sensors for robotics (contact, force and slip)
- Multiple closed kinematic loop robot manipulators
- Control configured vehicles (i.e., inherently unstable systems)
- Computer guided vehicles

IV) Bibliography

Papers (co)authored by Professor Angeles include:

1. Angeles, J., Spatial kinematic chains, Analysis, Synthesis and Optimization, Springer-Verlag, Berlin, 1982.

2. Angeles, J., On the numerical solution of the inverse kinematic problem, to appear in the Summer issue of The International Journal of Robotics Research 1985.

3. Angeles, J., Iterative kinematic inversion of five-axis robot manipulators, Internal Report, Dept. of Mech. Engng. of McGill University, 1985.

4. Angeles, J., Rojas, A., On the use of condition-number minimization and continuation in the iterative kinematic analysis of robot manipulators, Proc. 5th IASTED Symposium Robotics and Automation, New Orleans (LA). 1984.

5. Angeles, J., Habib, M., Numerical schemes for the kinematic control of redundant robot manipulators, accepted for presentation at the 30th Int. Symposium Mini and Microcomputers and their Applications, to be held in Montreal, 1985.

6. Angeles, J., Synthesis of plane curves with prescribed local geometric properties using periodic splines, Computer-Aided Design 15(3):147-155, 1983.

7. Angeles, J., Alvarado, M.A., Curve synthesis with natural cubic splines, submitted to Computer-Aided Design, 1984.

8. Angeles, J., Chaoming, Z., Duarte, R., Ning, H. Reducing area and volume integrals to line integrals, submitted to Computer-Aided Design, 1985.

9. Angeles, J., Callejas, M., An algebraic formulation of Grashof's mobility criteria with application to linkage optimization using gradient-dependent methods, J. Mechanisms, Transmissions, and Automation in Design: Trans. ASME, 106: 327-332, 1984.

10. Angeles, J., Lopez-Cajun, C., Optimal synthesis of translating-follower cam mechanisms with prescribed functional constraints, Int. Symposium on Design and Synthesis, Tokyo, 1984.

11. Angeles, J., Lopez-Cajun, C., Optimal synthesis of oscillating roller-follower cam mechanisms with prescribed function constraints, Proc. ASME Conference on Computers in Engineering, Las Vegas, 1984.

12. Angeles, J., Optimum synthesis of planar, spherical and spatial linkages for approximate function generation, submitted to Mechanism and Machine Theory, 1984.

Under preparation:

1. Angeles, J., A general procedure for mobility analysis of linkages.

2. Angeles, J., Linkage synthesis for minimum design error with maximum transmission quality, under mobility constraints.

Papers (co)authored by Professors Zsombor-Murray and Vroomen include:

1. Hudson, R., Vroomen, L.J., Zsombor-Murray, P.J., Operating system for hybrid BD/microprocessor programmable controller, International Journal of Mini and Microcomputers, 4(3):58-62, 1982.

2. Levi, M.H., Vroomen, L.J., Zsombor-Murray, P.J., Modular programmable controllers using an intelligent reflexive interface, International Journal of Mini and Microcomputers, 5(1):1-6, 1983.

3. Zsombor-Murray, P.J., Vrooman, L.J., Hudson, R., Authors reply to "Comments on binary-decision based programmable controllers by Dr. D.J. Stewart", to be published IEEE Micro, February 1985.

4. Zsombor-Murray, P.J., Vroomen, L.J., Hudson, R., Le-Ngoc, T., Authors reply to "Comments on binary-decision based programmable controllers by Mange, Sanchez and Thayse", to be published IEEE Micro, February 1985.

5. Zsombor-Murray, P.J., Vroomen, L.J., Le-Ngoc, T., Hudson, R., Holk, P., Binary-decision (BD)-based programmable controllers: concept, design and applications, Part 3, IEEE Micro, 3(6)24:38, December 1983.

6. Zsombor-Murray, P.J., Vroomen, L.J., Le-Ngoc, T., Hudson, R., Holk, P., Binary-decision (BD) based programmable controllers: concept, design and applications, Part 2, IEEE Micro, 3(5):16-26, October 1983.

7. Zsombor-Murray, P.J., Vroomen, L.J., Le-Ngoc, T., Hudson, R., Holk, P., Binary-decision (BD) based programmable controllers: concept, design and applications, Part 1, IEEE Micro, 3(4):67-83, August 1983.

Papers in Conference Proceedings:

1. Bubic, R.F., Vroomen, L.J., Zsombor-Murray, P.J., A hydropneumatic artificial skeletal muscle-like robotic actuator, CAN/CAM'85 Conf. Applied Mechanics, London, June 1985.

2. Hudson, R., Zsombor-Murray, P.J., Vroomen, L.J., Operating system for BD/microprocessor programmable controller, MIMI'82 International Symposium Mini and Microcomputers and Their Applications Conference, Cambridge, ACTA Press Code: 47, ISBNO-88986-037-8, pp. 1-4, July 1982.

3. Kucuk, A.C., Zsombor-Murray, P.J., Vroomen, L.J., Process control using a BD/microprocessor hybrid, MIMI'82 International Symposium Mini and Microcomputers and Their Applications Conf., Cambridge, ACTA Press Code: 47, ISBNO-88986-037-8, pp. 5-7, July 1982.

4. Kucuk, A.C., Vroomen, L.J., Zsombor-Murray, P.J., A binary decision controlled robotic balancer, CAN/CAM'83 Conf. Applied Mechanics, ISBNO-920049-00-1, Saskatoon, pp. 855-856, May 1983.

5. Levi, M.H., Vroomen, L.J., Zsombor-Murray, P.J., Computerized batch weighing systems using binary-decision based intelligent reflexive interface modules, MIMI'83 International Symposium Mini and Microcomputers and their Applications Conf., Lugano, ACTA Press Code: 56, ISBNO-88986-047-5, pp. 83-87, June 1983.

6. Levi, M.H., Vroomen, L.J., Zsombor-Murray, P.J., Modular programmable controllers using an intelligent reflexive interface, MIMI'82 International Symposium Mini and Microcomputers and Their Applications Conf., Cambridge, ACTA Press Code:47, ISBNO-88986-037-8, pp. 8-11, July 1982.

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McGILL UNIVERSITY

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I) Site Data

History and growth:

The Computer Vision and Robotics Laboratory was established in the late 1960's for the purpose of conducting research into pattern recognition and image processing. In the seventies, graphics was included as an area of interest and within the last eight years computer vision and robotics have been major concerns.

Facilities:

Unimation PUMA 260, IBM 7565 and Microbo Castor robots, Grinnell and Matrox vision systems, a VAX 11/780 and two VAX 11/750 computers, an Optronic Drum Scanner, various peripherals:

Source(s) and amount of funding:

NSERC Strategic Grants:	81/82	operating	$ 50,000
		equipment	50,000
	82-85	equipment	290,327
	82/83	operating	90,875
	83/84	operating	105,868
	84/85	operating	116,637

Additional funding is obtained through contracts.

Clientele:

Northern Telecom Ltd., Bell Northern Research, Digital Equipment of Canada Ltd., IBM Canada Ltd.

Plans for expansion:

The faculty is proposing to create a Robotics Institute by combining the Computer Vision and Robotics Laboratory with the Robot Manipulators Systems

Laboratory. Funding for the Institute was obtained from the Secretary of State ($700,000 Sept. 1984) and from the Quebec government's Centre de Recherche Informatique de Montreal (CRIM).

II) Personnel Data

Research Staff:	M.D. Levine	computer vision and robotics
	A.S. Malowany	robotics
	S.W. Zucker	computer vision and robotics
Associated Research Staff:	P.R. Belanger	robotics
	M. Frojmovic	
	P.R. Noble	
Visiting Scientist:	R. Hummel	
Staff:	D. Chau	Research Engineer
	C. Eskenazi	Systems Manager
	L. Everson	Research Associate
	F. Lew	Admin. Secretary
	R. Kinsella	Research Engineer
	M. Parker	Systems Programmer
	K. Sung	Research Engineer
	R. Quik	Technician (part time)
	J. Foldvari	Machine Shop (part time)

Graduate students:

At the present time, 42 graduate students (8 Ph.D., 34 M.Eng.) are associated with the Lab.

III) Research Activities

Principal Research Objectives:

The principal research objectives are twofold: one is to study various aspects related to robot vision with the ultimate intention of creating intelligent robots capable of functioning on the basis of sensory inputs; secondly, we are examining various aspects of robotic systems and control. The major application is the visual inspection, assembly and repair of hybrid circuits.

Areas of specialization:

Areas of specialization are: computer vision, visual inspection, sensors, collision avoidance and planning, computer systems for robot control, control algorithms for robots and hybrid circuits.

Research areas:

Computer Vision

An Expert System for Scene Interpretation

The objective of a computer vision system is the achievement of a correct and consistent interpretation of an image; interpretation meaning in the sense of a description of the given picture or scene, i.e. "seeing and naming". Previous research at this facility has been directed towards such a system but as two disjoint systems, the low level segmentation process and the high level interpretation. Currently, research is concerned with the development of an integrated system with top-down feedback.

A modular computer vision system of this nature is presently under implementation. A rule-based low-level image segmentation system was designed and has been implemented as a production system. This production system employs a fuzzy decision-making paradigm to set both the processing strategy and the data selection strategies. The basis for this dynamic mechanism is a number of performance parameters that are designed to measure the quality of the segmentation at any instant. This system, re-implemented in the production language OPS5, comprises the low level processing stage of this computer vision expert.

As a modular entity, the high level processing stage will employ a cooperative and competitive strategy to achieve labeling consistency. Particularly, interest is given to the initial inferences made about the possible labelings of regions in the image based upon integration of several bodies of evidence and its sensitivity to the relaxation process. The success of the high level interpretation is obviously dependent upon the resulting segmentation. Subsequently, a facility is necessary to provide for the refinement, coarsening or correction of the segmentation based on the interpretation. Such a mechanism employing fuzzy reasoning about the combined evidence from the low level segmentation and high level interpretation is proposed.

Several issues are involved in the development of such an "expert system". Foremost is the representation of a computer vision system as an expert. The central issues from an artificial intelligence perspective are those concerning the creation and management of a knowledge base, the utilization of inexact or plausible reasoning schemes as inference mechanisms and the encoding, organization and use of strategies.

Inferring the Shape of Three Dimensional Objects

Identification and recognition of objects in a scene is a difficult problem in computer vision. In particular, the recovery of the shape of objects and the ability to represent them presents intriguing problems. In the recent past, the shape of objects has been inferred from shading contours, texture, etc. However, these computational methods were highly constrained, requiring that the lighting conditions be known and only certain classes of objects were analyzed.

Given the restrictions of these methods, recent focus has been placed on the use of three-dimensional sensors such as range finding devices to recover

depth and some information of the shape of objects. These devices tend to be very expensive and generally function only in a small restricted environment.

At CVaRL, the aim is to investigate various 3D cues available from a 2D image of a scene. Despite the recent work with the "shape from" methods and the current interest in 3D sensing, it is felt that there are many geometric cues that could be identified and investigated further. It is these geometric cues that will aid in the segmentation of an image, the recognition of objects, and possibly the 3D representation of these objects. These issues are currently being investigated.

Computing and Interpreting the Shape of Moving Objects in 3D

The problem of representing and computing the three-dimensional shape of an object from images of that object in motion is examined. In particular, there is interest in the representations of shape at different levels of abstraction and the computational process by which this is accomplished. Specifically, the problem has been broken down into four sub-problems: the computation and representation of visible surfaces from a single view, the estimation of object or viewer motion relating adjacent views, the reconstruction of the object's surfaces in 3D object-centered coordinates, and the inference of the volumetric model implied by these surfaces.

The result of this research is a hierarchical representation for shape and a computational model by which this representation is computed from a sequence of images. Surfaces and their intrinsic properties are represented by what we call Dynamic Intrinsic Images. These are intrinsic images in the conventional sense, but include an extension in the form of a linear transformation which maps viewer-centered features into an object-centered co-ordinate system. From these dynamic intrinsic images can be abstracted an object's surfaces into a volumetric representation of the object by applying constraints imposed by the differential geometry. The approach is to decompose surfaces into constituent patches delineated by extrema in the surface normal curvature. The underlying volumetric structure is then inferred by fitting the appropriate geometric primitives based on properties of the surface patch.

This theory has been implemented and tested as a computer vision system (the McGill 3D Interpretation Testbed) for working the real objects in motion in front of a TV camera or computer generated images of the same. The latter option provides a means of analysis of the model by allowing the comparison of ideal versus estimated data. There has been success in experiments with smooth, solid objects and investigation currently addresses biomedical applications in which the geometric structure of blood platelets is to be reconstructed from images of their motion under a microscope.

A Rule-Based Low Level Image Segmentation System

A major problem in computer vision is the segmentation of images of natural scenes. This research project presents a new approach to this problem which is based on the design of a rule-based expert system. Expert knowledge about the low level properties of an image is formulated into production

rules. A number of processes employ these rules to segment the image into uniform regions and connected lines. Meta-knowledge rules control the order in which knowledge rules are matched, the strategy of processing and the focus of attention. A set of performance parameters which measures the quality of the segmentation at any instant determines the rule ordering and the focus of attention strategies. Experiments with the knowledge rules has resulted in the identification of an optimal set based on segmentation quality and processing efficiency. Overall system performance has been shown to be qualitatively and quantitatively superior to previous segmentation algorithms.

Currently, the segmentation expert has been partially rewritten in the production system programming language, OPS5. This module serves as the low level system of a knowledge based expert system for scene interpretation.

Deblurring Gaussian Blur

Realistic imaging systems introduce Gaussian degradation which is modeled by convolution against a Gaussian point spread function (e.g. computerized tomography). The Lab is concerned with the study of the inverse of this process, or Gaussian de-blurring. Since the optimal inverse as a convolution filter is not physically realizable, a pseudoinverse formulation based on a Hermite polynomial approximation is used. The result for the third order approximation strongly resembles the Laplacian of a Gaussian, while higher order approximations have additional side lobes.

Currently, the application of this theoretical framework is being studied. The translation of the deblurring problem to the discrete domain involves certain numerical considerations. As a first approach, the theory directed to the discrete case has been applied based on the fact that, in the limit, the discrete kernel approaches the continuous kernel. From this perspective, different discrete approximations are studied with respect to numerical stability and performance by varying the extent of blur and the order of approximation. As a second, and alternate, approach, the deblurring problem is considered exclusively from a discrete point of view. The analytic inverse of the discrete blur operator has also been found. The experimental results for this operator are extremely good and promising.

The Local Structure of Image Discontinuities in One Dimension

A new approach to locating discontinuities in one-dimensional cuts through idealized images is introduced. The approach is based on an estimation-theoretical extension of the mathematical definition of continuity, as applied to sampled, piecewise smooth (C^1) functions corrupted by noise (model for one-dimensional cuts through idealized images). This extended definition implies that discontinuities cannot be located without simultaneously determining their local structure (the structure of the uncorrupted function in a local neighbourhood about the discontinuity). Thus the problems are inseparable, and assuming that all discontinuities have the same local structure leads to incorrect results. Local structure is important for vision

because it can be used to guide the interpretation of the physical event causing the discontinuity, as well as providing additional constraints for the stero and motion correspondence problems.

Optimal Curve Finding

The feature detection process is often viewed as a two-stage process: images are initially convolved with one or many operators, and then the results of these convolutions, the operator responses, must be interpreted in terms of a consistent world model. Ideal feature detectors, if they existed, would always respond in an unambiguous manner, even in the presence of noise. No such operators exist, however, so optimal interpretation schemes are being developed.

In the curve finding problem, the most natural first measurement is one that provides an estimate to the orientation of the tangent to the curve at a point. In the absence of noise, an elongated difference of Gaussians or an approximation to the second directional derivative, functions quite well. These are used to define operators to be convolved against an image. The operator's response is maximal when both the orientation and position of the operator correspond to those of a tangent to the curve. Hence, rotational and lateral maxima of the operator following convolution are searched for.

When the image is degraded by noise, this direct interpretation of the maxima into tangents to a curve is no longer possible. Consequently, a relaxation labelling technique is applied to the initial (unreliable) interpretations to correct the ambiguities that are introduced by the noise process. It is well known that the most difficult problem in the use of relaxation labelling techniques is the specification of the compatibilities between the labels at neighbouring nodes. The Lab has addressed this problem by assuming that a curve could be approximated by its osculating circle in a reasonably small neighbourhood. This assumption leads to a very natural formulation for the compatibility matrix, based on the notion of co-circularity. There is a sense in which it amounts to the introduction of an estimate of curvature as well as the tangent at each point.

Briefly, co-circularity is the relationship between two vectors tangent to a given circle. During the relaxation process, neighbouring tangents support each other more if they are co-circular than otherwise, within a neighbourhood which has been chosen to be of the order of 15 by 15 pixels. When the assumption that the curve may be approximated by an arc of circle within this neighbourhood is verified, particularly when such a large neighbourhood is used, the convergence of the process is more rapid than previous attempts.

Robotics Control

Manipulator Parameter Identification

It is often difficult to obtain dynamic constants such as moments of inertia and center of mass locations. In this project, a set of experiments is being designed in order that parameter identification methods be used to

estimate the constants. This requires a judicious choice of several operating points, plus the proper excitation signals. The scheme is being developed in detail for the PUMA geometry.

Use of Force Measurements for Position Estimation

Force measurements are often used as measured variables in force control loops. However, they can also be viewed as position and torque input-dependent quantities. Given point contact of a tool and a surface of known geometry, it is possible to use force measurements to estimate position. The arm dynamics are linearized about an operating point corresponding to the center of the work area, but the contact surface is not linearized. An extended Kalman filter is used to obtain the estimator. This scheme has been applied successfully to a simulated two-dimensional arm.

Automatic Time Scaling by Feedback

Time scaling of arm trajectories has been studied by Hallerbach, among others, with the objective of providing a single scaling that would allow a given spatial trajectory to be tracked without saturating the torque elements. Intuitively, it is felt that the parts of a given trajectory should be traversed at varying speeds, in order to use most of the available torque, but at the same time avoiding saturation. A scheme is being studied where the time scaling is changed according to the magnitude of the torque, by feedback. At this point, a theoretical stability analysis is being carried out for the case of a pure inertia with a single torque input and disturbance.

Trajectory Planning in Time-Varying Environments: TPP = PPP + VPP

How does one get from "here" to "there"? This is an everyday version of the trajectory planning problem. We solve it so often, and so intuitively, that we are seldom aware of the complexity underlying it. The goal in this project is to study this complexity in a manner that motivates a particular decomposition of spatial and temporal aspects. This, in turn, leads to a new algorithm for solving the trajectory planning problem in time-varying environments, an algorithm which is summarized with the equation: TPP = PPP + VPP. In words, the Trajectory Planning Problem consists of a static Path Planning Problem and a temporal Velocity Planning Problem.

What are the essential ingredients of a Trajectory Planning Problem (TPP), and how are they used? Consider the following scenario:

Suppose that you arrive early at a cocktail party. The party has just begun, and the hall is sparsely filled. There is plenty of room. You desire a drink, and glance around the hall to locate the bar. Except for avoiding an occasional piece of furniture, you walk straight toward it. However, as another person approaches your path, you slow down to avoid a collision, speeding up again to your normal gait after she passes.

This example, while clearly oversimplified, illustrates the key intuition behind the approach - in the presence of moving obstacles, both the path and the velocity along the path are crucial for collision avoidance. It

furthermore suggests an intuitive decomposition of the whole problem into two sub-problems: (i) planning the path to avoid collisions with the stationary obstacles, and then (ii) planning the velocity along the path to avoid collisions with the moving obstacles.

The above observations have been formalized in a way that leads to efficient algorithms both for mobile robots in the presence of mobile obstacles and for multiple manipulators sharing a common workspace. The lab is now extending the algorithms so they can deal with real uncertainty in the environment.

Stability of Decentralized PD Controller

In practice, manipulator control is done by independant PID controllers (one per joint). It is felt that this unsophisticated control structure works reasonably well because of: 1) light loads, which lead to relatively decentralized dynamics; and 2) considerable function. The dynamic stability of a 3-joint PUMA manipulator under PD (Proportional plus Derivative) control is being investigated, by assessing the local stability at operating points all over the work envelope. The objective is to see whether the near friction-free robots of the future will, in fact, require more sophisticated controls.

Manipulator Control Along a Trajectory

A theory of manipulator control using acceleration feedback has been developed. This theory leads to simple, independent control laws for each joint. Error bounds for the full nonlinear model have been obtained, all that is required are bounds on the elements of the inertia mating, the gravitational forces, and the coefficients of the quadratic velocity terms in the Coriolis forces. Acceleration is not to be directly measured, but estimated by Kalman filtering from position measurements. The control scheme is being tested on the CMU simulation program.

Robotic Repair

Robot Programming

The objective is the development of a user-friendly environment for the operation of an industrial robot facility. Major concerns are: the man-machine interaction, high level language, data-base requirement, error diagnostics, recovery, and expert system implementation. A graphic simulator output is also required. The system should address multiple robots, sensors and peripherals. An implementation of robot language task oriented primitives for the repair of hybrid circuits is in progress.

Hybrid Circuit Repair Consultant

The repair of defective hybrid circuits with robotic manipulators requires an appropriate control scheme. To fulfill this role, a hierarchical robot control system, known as the Repair Consultant, is under development. The Repair Consultant will consist of two major parts: (i) task planner and

(ii) action planner. Given a list of defects, the repair consultant is responsible for determining what repairs are necessary and how these repairs are to be carried out. The output of the Repair Consultant will be a detailed plan consisting of a stream of commands submitted to the lower levels of the repair robot hierarchy.

Repairing Printed Circuit Boards Using a Robot System

A user-friendly system is being developed for repairing of printed circuit boards by a robot system. The objective is the implementation of desired cuts in circuit board traces and addition of soldered wires. Cooperative robot tasks and computer vision are required.

Hybrid Circuit Assembly and Repair

This project deals with designing a user-friendly facility for the assembly and repair of hybrid circuit dies using both the PUMA 260 and the Microbo robots, microscope vision, desoldering and solder past dispensing. Data base, machine inspection requirements, and special tooling are included.

Robotic Systems

Networking and Hierarchical Control of a Robotic System

The robotic laboratory presently involves two robots and a number of mini and micro-processor systems for robot control and vision processing. The study addresses the design and stability principles for a hierarchical computer network. The Unix networking and multiprocessing facilities are being applied to this distributed system containing robots, vision, and intelligent sensors.

High Performance Vision Processors

In order to achieve real time vision performance required for robot applications, highly efficient and optimized computer systems are needed. One case involves the design of a multibus-compatible processor system exploiting the TMS320 microprocessor by Texas Instruments. Some basic vision algorithms will be developed. A second case involves the design of a high speed convolver based on a custom design VLSI chip. A systolic design is adopted allowing the realization of arbitrary convolver sizes. A multibus design for a 9 by 9 is expected.

Robot Control 'C' Library (RCCL) Implemented on a PUMA 260

During the past year, work has been underway to install and expand on a Robot Control C Library (RCCL), orginally developed during 1983 at Purdue University by Vincent Hayward and Richard Paul. This is a system consisting of a set of data structures and subroutines embedded in 'C' UNIX which provide a versatile set of primitives for controlling a robot. These include facilities for Cartesian motion, path control, and force feedback. Lab personnel are presently completing the installation of this software on a Unimation PUMA

260, and are now looking at implementing it on a Microbo high precision robot. A principal objective here is to provide a uniform research/programming environment available across several robots. An Intel 8086 version is being developed using the RMX86 Operating System.

Measurement of Position in Absolute Coordinates

Present schemes call for the on-line solution of the inverse kinematics problem to generate joint coordinator from absolute coordinates. The complexity of the calculation is one disadvantage, the fact that this is an open-loop scheme is another. Absolute accuracy requires very precise knowledge of the kinematic constants. If the position in absolute coordinates could be measured, one could do away with both disadvantages by using feedback. It is proposed to develop an acoustic sensor system using one or several acoustic transmitters on the hand and several receivers located about the boundary of the working area. Phase measurements are to be used to measure both the time delays and the sound velocity and, using Kalman filtering, to estimate positions.

Calibration of a Robot Workstation

The lab is involved in the repair and inspection of hybrid integrated circuits, a task which demands high precision and a variety of tooling. This study addresses the calibration aspects of the PUMA 260 robot, its peripheral feeders, tooling, and vision systems using microscope and mobile cameras.

Robotic Inspection

An Automated Visual Inspection System for Bare Hybrid Boards

The design of an automated visual inspection system for fault detection during the production of hybrid circuits boards in their bare stage is in progress. A rule-based system is used for the general management of the inspection system as well as in decision making about fault candidates. At this point the system works well for the conductor layers of hybrid circuits, and programs to separate different printed layers from images are operational. New analysis rules have to be written for layers other than conductors.

Intelligent Robot Control for Hybrid Circuit Inspection

A central issue to modern mass manufacturing is quality control. Manufacturers depend on sampling some of the finished products and using them as representative of the quality of the entire batch, an electronic component company would be in a much better competitive position if they could inspect and guarantee 100% of their finished product. The lab hopes to develop a general purpose robotic and vision inspection station. To be general purpose, the test station must be able to adapt to different products from different production runs as well as the various types of visual inspection actions to be performed on different parts of the product. A knowledge based system is required to keep track of all the visual data required and already acquired.

An expert' system is being developed to oversee the data acquisition programs. The expert system is made of two parts. First, a data base which represents the knowledge of the robot's general environment and in particular the specialized knowledge needed to define the subject of the inspection task. Second, a set of rules which apply the high level motion and vision programs as primitives to operate on (i.e., inspect) the environment. The set of rules will facilitate a high level description of robotic inspection tasks and interactive modelling of the environment.

Visual Inspection of Hybrid Circuits

A rule-based system for the inspection of hybrid circuit components is being developed. A significant problem is to determine the position of a discrete component on the circuit board from an image generated by a camera. This task is made difficult by the presence of a large number of reflective regions (i.e., solder joints, IC pins) which decrease the coherence of the digitized image. Secondly, a sequence of analysis programs designed to detect specific assembly defects are applied to the image. These faults include conductor defects, solder joint quality and component integrity. Finally, a report on the state of the component is generated.

Hybrid Circuit Component Positioning Using a PUMA 260

In order to visually inspect by computer the discrete components on a hybrid circuit board, it is necessary to first position the circuit at an arbitrary position and orientation in the three-dimensional workspace. The circuit is viewed by an array camera under magnification provided by a microscope. It may then be analyzed for solder joint quality, for example.

The purpose of this project is to use the PUMA 260 as a positioning and orientation device by incorporating vision feedback to compensate for its inadequate positioning accuracy. The feedback is used to assist in positioning a specific circuit pad under the microscope. The manipulator is also required to move the circuit in the vertical direction to provide automatic focus control based on the veiwed image. Another aspect under consideration is the avoidance of a collision between the hybrid circuit and the microscope while it is being positioned. A self-contained VAL program is being written for what is essentially a five-degree-of-freedom mechanical stage with automatic focusing.

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MONTRÉAL, UNIVERSITÉ DE

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I) Summary:

Robotics research is performed within the Laboratoire de Robotique et de Vision, which was established in 1982 with grants totaling $200,000 from the Government of Canada and NSERC. The research equipment situated in this laboratory includes: a PUMA 560 robot, CCD cameras, an IBM PC, and a network of Lisa and Macintosh computers. Also, the laboratory has access to a PDP 11/34 and VAX 11/750 computers. Advanced workstations are expected to be in operation in 1985 (Sun 2/170 with frame-grabber and VME/10 real time system).

II) Personnel Data

Principal Researcher:		
Prof. N.F. Stewart	Chairman, Dept. d'I.R.O.	robotics
Affiliated Personnel:		
D. Charbonneau	Technician	hardware
Prof. G. Gecsei	Professor	VLSI
M. Jacques	Technician	hardware
M. Maksud	Programmer Analyst	software
D. Thalmann	Professor	comp. graphics

In addition, 5 graduate students (all M.A.Sc.) conduct research.

III) Research Activities

Research areas include: failure recovery (fault tolerance), computer vision, path planning (collision avoidance), work cell simulation.

Software programs were developed for controlling a system of several robots (multi-arm robots) and a vision system.

IV) Bibliography:

A series of eight technical reports (in French) has been written describing the multi-arm control system and the associated controller.

Results of some of the robotics research performed at the Université de Montreal are published in the papers listed below:

1. Feeley, M., Stewart, N.F., Robotic vision and graphical display based on the IBM PC, Graphics Interface '83, pp. 97-101, 1983.

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I) Summary

Robotics research is conducted in the Laboratoire de la Robotique of the Faculty of Engineering. The laboratory, established in 1984, is equipped with a PUMA 560 robot with accessories, a CAD/CAM System with a CDC Cyber 815 computer and 6 Tektronic workstations. Funds for the laboratory have been obtained for 1984-85, from: The Université du Québec ($19,000), the Institut de Recherche en Santé et Sécurité au Travail du Québec ($14,000), and Northern Telecom Ltd. ($47,000). One research assistant is employed full-time in the Robotics Laboratory. Two Rhino robots, robotic accessories, tools and instruments will be acquired for the laboratory in the near future.

II) Personnel Data

Principal Researchers:

Dr. A. Jacob	Professor	Electical Engineering
Dr. K. Ghosh	Professor	Manufacturing Engineering
Dr. A. Kadima-Nzuji	Professor	Electrical Engineering
Prof. C. Perron	Professor	Mechanical Engineering
Dr. V. Rajagopalan	Professor	Electrical Engineering
Dr. F. Seha	Professor	Industrial Engineering
Dr. A. Sévigny	Professor	Electrical Engineering

In addition, 1 research assistant and 1 graduate student conduct research.

III) Research Activities

The research areas are: human-robot interaction and safety, robotic assembly, kinematic modelling and control, and arc-welding applications. Work is planned on the following topics: study of control systems for arc welding, inspection using artificial vision, simulation of the robot on a CAD system, insertion during assembly, and robot operator safety. Some research and development work is done in collaboration with Northern Telecom Ltd.

Development of robotic tooling for assembly of electronic components on P.C. boards and a safety evaluation of PUMA and ASEA teach pendants are considered to be the major accomplishments to date. The two most important areas of activity in the laboratory are the robotization of electronic assembly and safety aspects of robotics.

IV) Bibliography

1. Ghosh, K., Robotic assembly of printed circuit boards, To be presented at the 4th Canadian CAD/CAM & Robotics Conference, Toronto, Ontario, 1985.

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3. Ghosh, K., Bonenfant, M., Application de la robotique dans l'assemblage des plaquettes de circuits imprimés, Accepted for 2nd Canadian Universities Conference on CAD/CAM, Montreal, Quebec, 1985.

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I) Summary

Robotics research is performed primarily in the Mechanical Engineering Department's CAM and Robotics Laboratory which was established in the summer of 1984. Research facilities available to lab personnel include: an Apple IIc controlled "Minimover-5" robot, an Autonumerics MK-2 vertical CNC milling machine, a CNC lathe (Baxter Technologies - Future Builder), a VAX 11/730 computer, several microcomputers, terminals, peripherals, access to a Computervision CAD/CAM system, and a locally built automatic assembly programmable device ("Robotus-2.5"). In addition, a five axis servo robot ("ERRICC") is scheduled for installation in May, 1985.

Funds for equipment were obtained from NSERC (1984-6, $7,500), from the Ministry of Education, Quebec (1984-6, $75,000), and from the Université de Sherbrooke (1985- , $17,000)

Contacts are maintained with the Universite Paris XII (Prof. C. Vibet), the Robotics Laboratory, UWIST Cardiff, located in Wales, United Kingdom (Prof. P.J.V. Drazan), and with the artificial vision group (Dr. S. Richard) located in the University of Sherbrooke's Department of EE. Some work is being done for local companies interested in production automation.

II) Personnel Data

Principal Researchers:

Prof. P.A. Bourasa	Professor	kinematic/dynamic modelling and control
Dr. M. Brezina	Associate Professor	CAD/CAM, robot design
Dr. Y. Van Hoenacker	Associate Professor	CAD/CAM

In addition, there are 2 graudate students conducting research.

III) Research Activities

In addition to the work done in the CAM and Robotics Laboratory, robotics

research is also conducted in the Department of Electrical Engineering by Dr. S. Richard in the area of artificial vision.

The research areas of interest include: control, robot design, compliant wrist design, and robotic applications. The primary research objectives are: to develop an instrumented remote centre compliance (IRCC) device to be used in assembly operations, kinematic and dynamic modelling of manipulators, and system simulation. The areas of specialization include: trajectory planning and control, kinematic and dynamic modelling, control of robots, development of instrumented compliance devices, and planning of assembly operation using force control.

A major computer program was written in BASIC and Assembler for operating the remote centre compliance device. A kinematic and dynamic simulation program is being developed in FORTRAN for robots with up to six degrees of freedom.

Design and construction of an automatic programmable assembly device, structural design of a four degrees of freedom robot, construction of RCC devices, and design and construction of an IRCC assembly system are considered to be the major accomplishments of the laboratory to date.

IV) Bibliography

1. Brezina, M., Khan, M., Robotic assembly of compliantly supported rigid parts, accepted for presentation at the 4th Canadian CAD/CAM & Robotics Conference, Toronto, June 19th, 1985.

2. Khan, M., Brezina, M., Assemblage des pieces rigied par robots, to be presented at the 53th Congress ACFAS, Chicoutimi, May 1985.

3. Several internal reports related to the Minimover-5 use and programming.

TECHNOLOGIE SUPÉRIEURE, ÉCOLE DE

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I) Summary

Robotics activity at the school is primarily directed towards robotics teaching. A Bachelor of Technology Degree is offered in Automated Production Technology. Educational/research facilities include: a Microbot Teachmover robot, an ASEA IRB6/2 robot, a compacts 5 NC machine, an IBM 4331 computer and H.P. based CAD/graphics systems. Expansion plans call for the installation of a 3-axis NC machine and hopefully a PUMA 260 robot (summer 1986). Funding, at this time, is provided by the school; however, contract funding is planned for next year.

The principal researchers are Professors LeQuoc and My Dao and Mr. Bouchard (Chairman, Department of Automated Production). Prof. LeQuoc's research interests lay in off-line programming and vision. Prof. My Dao conducts research in manufacturing control while Mr. Bouchard is interested in robot vision and is actually constructing a vision system. The group's research objectives include: the development of a low-cost, light-weight, high-speed vision system for robots, and the development of hardware and software for off-line programming of industrial robots.

II) Bibliography

None at this time.

TECHNOLOGIE SUPÉRIEURE, ÉCOLE DE

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I) Summary

The Department of Automated Production, established in 1983, has a faculty consisting of Professors Bouchard (Director, Automated Production), Olivier (Ind. Eng.) and Sabourin (Elec. Eng.). Research facilities include: an ASEA robot, a vision system (Intel 380 and frame grabber), a CAD/CAM system and an H.P. 9000 computer. The department is funded by the Education Agency of Quebec ($485,000).

The group's research objectives address the areas of CAD, CAM and CIM; however, research areas involve robotics as they apply to those technologies. To date, research developments consist of setting up a "vision laboratory" in which work on the inspection of 2-D industrial parts is proceeding.

II) Bibliography

None at this time.

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I) Summary

Robotics research is performed in the Departments of Mechanical Engineering, Electrical Engineering and Computer Science within the Faculty of Engineering.

The Mechanical Engineering Department is closely tied to the New Brunswick Manufacturing Technology Centre (M.T.C.) which links together the University of New Brunswick, l'Université de Moncton, Community Colleges at Moncton, Saint John and Bathurst, and the Research and Productivity Council (Fredericton) under the auspices of the Provincial Department of Commerce and Development. The objective of the Manufacturing Technology Centre is to conduct research and development work, and provide training and advisory assistance for industry in the area of CAD/CAM. Funds for the Centre are provided by the Federal and Provincial Governments, NRC and NSERC.

In the laboratories of the Mechanical Engineering Department, research facilities include: a PUMA robot, a Bridgeport CNC machine, a VAX 11/750 computer, and a number of CAD workstations and plotters.

II) Personnel Data

Principal Researchers (Faculty of Engineering):

Prof. D.J. Bonham	Chairman, Mech. Eng.	CAD/CAM robotics
Dr. R. Balasubramanian	Prof. (Elec. Eng.)	multivariable digital control
Dr. R. Doraiswami	Prof. (Elec. Eng.)	digital control
Dr. L. Goldfarb	Prof. (Comp. Sci.)	pattern recognition
Dr. B. Kunz	Prof. (Comp. Sci.)	image processing
Dr. E.W. Richards	Director, M.T.C.	CAD/CAM, robotics
Prof. L. Torfason	Prof. (Mech. Eng.)	kinematics
D. Travers	Research Engineer	CAD/CAM, robotics
Dr. D. Wasson	Chairman, (Comp. Sci.)	pattern recognition, robotic vision

III) Research Activities

Robotics research in the Mechanical Engineering Department is performed by Professor D.J. Bonham, Chairman of the Department, Dr. E.W. Richards, Director, M.T.C., and D. Travers, Research Engineer. The research is mainly application oriented. A robotic welding cell is being developed for industry using a PUMA robot to perform the welding operation. A fixture, holding the workpiece, was designed for this application. This fixture, having two revolute joints, can rotate the workpiece so that the welding is always performed in a horizontal direction. A flexible workcell combining the PUMA robot and an N/C milling machine has also been developed. This workcell incorporates sensors, supervisory control, and automatic locating and holding devices.

Professor L. Torfason of the Mechanical Engineering Department is involved in the design of robotic modules including fingers, wrists, elbows, shoulders, etc. This design and development work takes place in co-operation with the Centre of Robotics Research at the University of Florida, Gainsville, where Professor Torfason spends a considerable amount of time each summer. Patenting of the modules is planned. Professor Torfason also conducts research in the area of robot kinematics. In particular, the determination of optimal paths in robotic workspaces is being investigated.

In the Department of Computer Science, Dr. W.D. Wasson, Chairman of the Department, Dr. B. Kunz and Dr. L. Goldfarb are actively working in the area of image processing and pattern recognition. This work is potentially important for robotic applications. Image aquisition systems and software to restore, enhance and aid a user in the manipulation of images are being developed. Dr. Goldfarb's work on pattern recognition is considered significant. A number of publications are available. The Department's laboratory contains vision systems, and a small Mitsubishi RM101 robot.

In the Electrical Engineering Department, Dr. R. Doraiswami works on the development of a digital controller for a closed loop system containing a digital filter and a digital stabilizer. The objective of the research is to control machines, including robots, so as to achieve rapidity and precision. Dr. Balasubramanian of the Electrical Engineering Department also works in the area of multivariable digital control, including the control of N/C machines using a microprocessor.

Research areas include: geometric modelling, vision systems, flexible manufacturing systems, robotic welding, sensor development, adaptive control, kinematics of robots, workspace modelling, image processing, pattern recognition, digital control, design of robotic moduler and optimal path determination in robotic workspaces. Development of a flexible work cell and a robotic welding cell are considered the most important accomplishments to data.

IV Bibliography

1. Bonham, D.J., The role of industrial robots in CAD/CAM, Miconex 82, Invited paper.

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I) Summary

The Robotics Lab, in addition to first year introductory robotics courses, was established in 1984 with funds provided by a $20,000 grant. Research facilities consist of a Rhino XR-1 robot, a Microbot robot, an educational CNC machine, and a few Apple II computers. Should funds become available, the facilities would be expanded to include two industrial robots.

Professor Kujath's research interests include: development of flexible structures and optimization of robot structures. In an effort to produce a multi-degree of freedom "snake-like" robotic arm for inspection applications, several flexible mechanical sections have been constructed.

II) Bibliography

None at this time.

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Telex: 019-21566

I) Summary

Professor Kusiak has been involved in robotics research for approximately five years. Although no research facilities are available within the Department of Industrial Engineering, his associations with the Toshiba Corp. and the Okuma Factory in Japan have been very productive. Professor Kusiak's research interests include: manufacturing system, materials handling systems, vision systems and robotics. His principle objective is the development of high-level robot programming languages. Major developments include models and software products for the planning and scheduling of robots, NC machine tools and automatic guided vehicles. Two graduate students are supervised by Prof. Kusiak.

II) Bibliography

Books:

1. Kusiak, A., Modelling and Design of Flexible Manufacturing Systems (Kusiak, A., ed.) (to be published by Elsevier early 1986).

2. Kusiak, A., Flexible Manufacturing Systems: Methods and Studies (Kusiak, A., ed.) (to be published by North-Holland Publ. Co. early 1986).

Journal Papers:

1. Grossechallau, W., Kusiak, A., An expert system for design of material handling system, Material Flow, June/July 1985 (accepted for publication).

2. Kusiak, A., A unified pattern recognition approach to the representation of part geometry, Int. Journal of Production Research, 22(5): 823-830, 1984.

3. Kusiak, A., Analysis of integer programming formulations of clustering problems, Image and Vision Computing, 2(1):35-40, 1984.

4. Kusiak, A., Material handling in flexible manufacturing systems, Material Flow, June/July 1985 (Accepted for publication).

5. Kusiak, A., The part families problem in flexible manufacturing systems, Annals of Operations Research, 1985 (accepted for publication).

Proceedings Papers:

1. Kusiak, A., Robot applications in flexible manufacturing systems, Proceedings of the Robot 8 Conference, Detroit, MI, pp. 3.1-3.13, June 1984.

2. Kusiak, A., Robots and vision systems in flexible automation, Proceedings of the Annual Conference of the CSME, Halifax, N.S., pp. 207-224, 1984.

3. Kusiak, A., Production control in flexible manufacturing systems, in: Rotary Metalworking Processes, (Kobayashi, E., ed), North Holland, pp. 473-481, 1984.

4. Kusiak, A., Modelling and solving of object grouping problems in CAD/CAM, Proceedings of the Ninth Canadian Congress of Applied Mechanics, Saskatoon, pp. 785-786, May 1983.

3.2 Training Centres

Presented in this section are the robotics training centres. These are colleges within Ontario (although others may exist in other provinces) at which robotics technology programs are offered. It should be noted that the universities presented in the preceding section are also training centres, although university training is more theoretical in nature, dealing with control, design, principles of operation, and the like.

The mandate of the colleges is to teach, train and transfer technology. While the technology programs are of little interest to the robotics research community (save maybe for industrial management), it is the robotics teaching facilities available at the colleges which are a consideration in that they could be made available to industry or the universities for research purposes. Since it is these facilities which were deemed to be of principal interest for the purposes of this guide, the format for the college entries includes only robotics training facilities and robotics personnel.

ALGONQUIN COLLEGE

200 Lees Avenue
Ottawa, Ontario
K1S 0C5

Mr. C.N. Tite
(613) 598-3303

Robotics technology program established: November 1984

I) Robotics Teaching/Training Facilities

IBM 7545 robot
Zenotech Vision System
Orcatech 2000 CAD System

II) Robotics-related Personnel

C.N. Tite	Co-ordinator	CAD/CAM
P. Casey	Research Assistant	computer graphics

CENTENNIAL COLLEGE
OF APPLIED ARTS & TECHNOLOGY

P.O. Box 631, Station A
Scarborough, Ontario
M1K 5E9

Mr. N.G. Eley
(416) 752-4444

Robotics technology program established: 1982 - 1983

I) Robotics Teaching/Training Facilities

Cincinnati-Milacron Laboratory	(1,500 sq. ft.)	C-M T3 Robot
PUMA Laboratory	(1,375 sq. ft.)	2 Puma 560 Robots
PRAB Laboratory	(750 sq. ft.)	PRAB 4200 Robot
ASEA Laboratory	(150 sq. ft.)	ASEA MHU Junior Robot
Rhino Laboratory	(875 sq. ft.)	15 Rhino robots
Pneumatics Laboratory	(1,200 sq. ft.)	

IBM-PC and Digital Mink (PDP-11) computers; extensive robot maintenance equipment

II) Robotics-related Personnel

P. Bentley	Chairperson, Industrial Motive Power	fluid power, robotics
N. Eley	Dean, Transportation & Power Technology	
J. McCarron	Co-ordinator	
R. Pavlovich	Program Director	fluid power, robotics
R. Day		fluid power, robotics
W. Elehew	Teaching Master	ASEA robot, computers
G. Noble	Teaching Master	PUMA robots, end effectors
T. Sanderson	Teaching Master	CINCI robots, electronics
		Rhino robots mechanical

RYERSON POLYTECHNICAL INSTITUTE

Centre for Advanced Technology Education (CATE)

350 Victoria Street
Toronto, Ontario
M5B 2K3

Mr. D. Hall
(416) 979-5106

Centre established: January, 1984

I) Robotics Teaching/Training Facilities

IBM 7535 Robot
ASEA IRB 6/2 Robot
IBM 4381 - based CAD system (12 Monitors and Peripherals)

II) Robotics-Related Personnel

Williams	Program Director - FMS/CIM	CAD
Carter, W.	Professor	Robotics
Miscocks, P.	Professor	Vision Systems
Nemeth, A.	Professor	Robotics

SENECA COLLEGE
OF APPLIED ARTS & TECHNOLOGY

1750 Finch Avenue E.
North York, Ontario
M2J 2X5

Dr. D. E. Coates
(416) 591-5050
Telex: 06-9[illegible]659

Robotics technology program established: 1984

I) Robotics Teaching/Training Facilities

Robots:	Microbot, Hitachi Technovate, ADEPT1, Seiko PN 700
CNC equipment:	Mycentre 2 - 3 axis vertical mill, Okuma & Howa Act 4 CNC lathe
CAD equipment:	Auto-trol S7000, S5000 on VAX II/780 & Tektronix PLOT 10
CAM equipment:	MDSI NC Graphics (including Compact II), ICAM CAM.APT
Simulation equipment:	ANEVENT, DYNAMO, SIMAN, GPSS
FEM/FEA:	ANSYS

II) Robotics - Related Personnel

D. Coates	Chairman, Mech. Engineering	Simulations
C. Flacks	Dean of Technology	Electronics Control Systems
G. Dunsford	Teaching Master	Manufacturing Processes Planning
M. Peros	Teaching Master	Electromechanical Systems

4.0 THE RESEARCH AND DEVELOPMENT EFFORT OF THE GOVERNMENT AND INDUSTRIAL SECTORS

In this chapter sites conducting robotics R & D activities in the government (Section 4.1) and industrial (Section 4.2) sectors are profiled. A single format was selected for all of the entries. This format summarizes the site's background, R & D activities, and facilities; presents additional contacts and, in the few applicable cases, presents a bibliography of the site's publications. As with those in Chapter 3, these entries are arranged geographically, by province, and alphabetically within a province.

4.1 Government Sector

Robotics R & D activity within the government sector exists within research laboratories associated with (established by) federal government departments and within centres established by provincial governments. Both these groups are addressed within this section.

ALBERTA RESEARCH COUNCIL (ARC)

Industrial Development Department
Industrial and Engineering Research Division

4th Floor, Terrace Plaza
4445 Calgary Trail South
Edmonton, Alberta
T6M 5R7

Mr. C. Harrison
Industrial Technology Advisor
(403) 438-1555

I) Summary

The Alberta Research Council has recently established a facility to assist the manufacturers of that province to increase their awareness of advanced manufacturing systems and implement such systems in their own operations. The facility will involve itself in the level of research and development appropriate to the need as that need becomes apparent. The ARC is presently engaged in extensive R&D in many areas not related to manufacturing. Originally established to develop the province's mineral resources (oil and gas), the Council has succeeded in advancing the technology of mineral extraction used in the province.

ATOMIC ENERGY OF CANADA LTD. (AECL)
CHALK RIVER NUCLEAR LABORATORIES (CRNL)

Chalk River, Ontario
K0J 1J0

Mr. N. Smith
Manager, Research Contracts
(613) 584-3311
Telex: 053-34555

I) Summary

The Chalk River Nuclear Laboratories were formed in 1944 and were part of NRC until 1952 when AECL was formed as a crown corporation. CRNL now has a staff of over 2,000 people, including 400 engineers and scientists. Several branches of the laboratories are involved in robotics R&D.

The Fuel Materials Branch is involved in the implementation of robotic technology to automate nuclear fuel processes. Their primary objective is to develop the technologies necessary for the low-cost high-volume manufacture of mixed oxide fuels for CANDU reactors. To this end, the branch has interfaced a wide range of analog sensors to the data collection system for performance evaluation. These sensors include inductive-proximity, infrared, ultrasonic, optical, linear-variable differential transducers, piezoelectric load cells, and strain gauges. The branch assesses robots and end-of-arm tooling for suitability for automated nuclear fuel manufacturing, and tests feedback control of robotics tooling under simulated conditions. They anticipate that their program will generate knowledge of the effects of long-term exposure of ionizing radiation on typical robotics components, as well as furthering the state of real-time adaptive control of robots and teleoperator handling techniques, with applications in remote inspection and maintenance. Branch facilities are equipped wih a Cincinnati Milacron T3 Model 766 and Version III controller, a Unimate Model 103 assembly robot, and Apple/Isaac Data Acquisition system, and a prototype pellet sorting/measuring station.

The Mechanical Equipment Development Branch of CRNL is not currently involved in research. It specializes in the design, fabrication and development of special-purpose automated tooling for the inspection and maintenance of nuclear facilities, in cooperation with other groups at CRNL. Their work includes inspection and repair tooling for reactor core inspection and the large-scale replacement of nuclear fuel channels.

The Non-destructive Testing Development Branch develops specialized automated and semi-automated NDT systems for remote inspections. They have developed numerous systems for microprocessor based control and data handling, and foresee eventual transfer of their equipment technology to equipment

manufacturers and industry. Its facilities house various computers, including the PDP11, two multibus systems, two M6809 development systems, and an HP-1000, as well as large electronic/mechanical workshops.

The Reactor Control branch develops computer-based systems for control, safety and data acquisition in nuclear and non-nuclear applications. The branch has expertise in advanced control theory and real-time computing, and is prepared to participate in the mathematical modelling, computer simulation, and design and implementation of robot control systems. The Dynamic Analysis Laboratory of the Reactor Control Branch houses a DEC VAX-11/750, PDP-11/45, and PDP-11/55 used in conjunction with two AD-5 analog computers.

II) Additional Contacts

M. Deverno	Resident Engineer	Non-Destructive Testing
H. Licht	Resident Engineer	Non-Destructive Testing
E.O. Moeck	Branch Head	Nuclear Control

III) Bibliography

1) May, F.B., Surette, R.A., Wood, J.C., Robot-assisted manufacturing of gamma-active nuclear fuels: research and development phase, 1983.

2) Wood, J.C., Surette R.A., Automated fabrication for advanced fuels, 1984.

3) Wells, N.S., An automated eddy current in-service inspection system for nuclear steam generator tubing, 1981.

ENERGY, MINES AND RESOURCES CANADA (EMR)
CANADA CENTRE FOR MINERAL AND ENERGY TECHNOLOGY (CANMET)

555 Booth Street
Ottawa, Ontario
K1A 0G1

Mr. T.R. Blake
Mineral Technology Information Officer
(613) 995-4059

I) Summary

CANMET is the research and development branch of the federal department of Energy, Mines and Resources. As such, one of its objectives is to complement industrial R&D activity in order to improve the economic performance and productivity of the non-renewable resources industry. CANMET is involved in a program for the development of advanced technology for mining. This program can be described in four parts:

1) evaluation of industry needs
2) development of improved, automated, or remotely-controlled equipment to meet immediate needs
3) development of mine design to facilitate the use of advanced technology
4) long term research of technology to support integration of robotics into comprehensive automated mining systems

The program involves the CANMET staff, consultants working under contract to the centre, and mining and equipment industries collaborating with the centre. The current focus of the program is on underground, hard-rock mining and the effort is expected to be fully applicable to uranium mining. CANMET's mining research laboratories are compiling an inventory of all current mining R&D projects in Canada for circulation to the industry

INCO is presently under contract to CANMET to develop and produce a prototype bar-and-hammer robot for initial use in the hazardous operation of punching tuyeres in a copper converter. Eventual application will be in scaling and conveyor-clearing tasks. Mining Resource Engineering Ltd. has been contracted to develop an interactive software system for direct coupling with drills and explosives loading equipment. CANMET has been involved for ten years in a project to develop operational monitoring and control capability, particularly in the area of mine environment sensing and control systems. The result is the CONSPEC Senturion comprehensive mine monitoring system. Current activities involve collaboration with Westar Resources in Sparwood, British Columbia, to demonstrate a CONSPEC unit modified for the explosive methane environment of a coal mine. CANMET is also active in sensor development for key operational parameters, which involves mine environment

monitors to measure diesel exhaust, airborne dusts, noxious gases, and radiation.

CANMET has a total staff of 800 and has a range of laboratory equipment that is unique, or nearly so, in Canada.

II) Additional Contacts

J.T. Jubb	Deputy Director General
T.D. Brown	Director - Coal Research Laboratories
W.M. Erickson	Director - Physical Methalurgy Research Laboratories
W.A. Gow	Director - Mineral Sciences Laboratories
B.I. Parsons	Director - Energy Research Laboratories
J.E. Udd	Director - Mining Research Laboratories

III) Bibliography

A cumulative catalogue of all CANMET publications still in print is in preparation. Annual catalogues are also available.

NATIONAL RESEARCH COUNCIL
OTTAWA, ONTARIO K1A 0R6

NRC is a federal government research laboratory with a diverse set of activities in many fields of science. Research and development in robotics technology is coordinated within three of its Engineering Laboratory Divisions as described below.

NATIONAL AERONAUTICAL ESTABLISHMENT (NRC/NAE)

Building M-60, Montreal Road
Ottawa, Ontario
K1A 0R6

Dr. G. M. Lindberg
Director
(613) 993-2427

I) Summary

The aeronautical section of NRC is developing a 3D vision system with Diffracto in Windsor. The system sets a target on a known geometry or physical point and calculates the third dimension from this data. NAE is also working on the Canadarm for the shuttle program and is continuing their efforts in robotic control systems.

DIVISION OF ELECTRICAL ENGINEERING (NRC/DEE)

Building M50, Montreal Road
Ottawa, Ontario
K1A 0R8

Dr. J.Y. Wong
Director
(613) 993-1384
Telex: 053-4134

I) Summary

DEE's research in the robotics field began in 1981 with the aim of developing sensory-based robotics technology suitable for flexible assembly.

The research effort has since expanded to involve 16 full-time researchers. The orientation of these activities is largely towards the longer term in the form of core support for future generations of robotics technology, rather than an applied focus over the short to medium term. Their approach to robotics is from the point of view of sensor based control of a realtime system, with a primary interest in how to express this control in terms of viable computer systems.

In support of this goal, the division has developed a multiprocessor computing system architecture and focuses on problems in real-time control in its experimentation using this system with robots and sensors. Complementing this effort is work in sensor development (primarily vision) and investigation of techniques for planning and programming sensory-based robot tasks.

Among the research areas of DEE are computer vision/object recognition, a laser-based 3D range camera, knowledge-based task planning and collision avoidance, and advanced workstations for robotics task modelling and simulation. Specialty areas include parallel architectures and realtime computing, optical processing and optoelectronics, computer graphics, man-machine interaction, image processing, and artificial intelligence.

The division does not provide fee based consulting services, but does liaise with industry, primarily for the purpose of supporting new product opportunities through transfer of technology from its laboratories to industry. DEE conducts research of a higher financial risk than is normally undertaken by the private sector, with the objective of demonstrating the technical feasibility of its projects. DEE's research is complementary to that of other centres. It communicates with other research laboratories including: the System Laboratory of NRC/DME, the Robot Welding Laboratory of NRC/IMRI, and various laboratories at Ontario and Quebec Universities.

The divisions facilities include: 3 PUMA 560 robots, 2 VAX computers, a symbolics 3600 LISP MACHINE, 3 multiprocessor computing systems, a laser and optical processing laboratory, display systems, specialized peripherals for graphics, image processing and sensor development.

II) Additional Contacts

N. Burtnyk	Section Head	Computer Graphics
J. Domey	Section Head	Electronics Engineering

III) Bibliography

Conference Publications:

1. Gentleman, W.M., If only the hardware ... (a software designer's lament), Proc. IEEE Int'l Workshop on Computer System Organization, March 1983.

2. Rioux, M., 3D camera based on synchronized scanning, Proc. 13th ISIR and ROBOTS, April 1983.

3. Rioux, M., Compact high speed 3D vision scanner for robotics applications, Proc. 2nd Can. CAD/CAM and Robotics Conf., May 1983.

4. Gentleman, W.M., Using Harmony, Proc. CIPS Session '84, May 1984.

5. Blais, F., Rioux, M., Poussart, L., A very compact 3D camera for robotics applications, Proc. Conf. on Machine Vision, Winter '85, March 1985.

6. Kasvand, T., Oka, R., Dhome, M., Rioux, M., Segmentation, learning and recognition of objects in range camera images, Proc. 4th Can. CAD/CAM and Robotics Conf., June 1985.

7. Tanner, P. Borrel, P., Liégeois, A., Automatic generation and representation of the work area of a robot arm in a CAD/CAM system, Proc. 4th Canadian CAD/CAM and Robotics Conf., June 1985.

NRC Laboratory Reports:

1. Abdelmalek, N.N., Robotics Bibliography: 1970-1980 (Part A) Applications of Industrial Robots, ERB-935, 1981.

2. Abdelmalek, N.N., Robotics Bibliography: 1970-1980 (Part B) Robotics Research and Development, ERB-936, 1982.

3. Abdelmalek, N.N., Robotics Bibliography: 1981-1982 (Part A) Applications of Industrial Robots, ERB-959, 1983.

4. Abdelmalek, N.N., Robotics Bibliography: 1981-1982 (Part B) Robotic Research and Development, ERB-960, 1983.

5. Green, D., Chorus - A Multiprocessor Architecture for Real-time Control Applications, ERB-964, 1983.

6. Elgazzar, S., Green, D., and O'Hara, D., A Vision-based Robot System Using a Multiprocessing Controller, ERB-971, 1984.

7. Elgazzar, S., Efficient Solution for the Kinematic Positions for the PUMA 560 Robot, ERB-973, 1984.

8. Elgazzar, S., Efficient Solution for the Kinematic Velocities and Accelerations for the PUMA 560 Robot, ERB-974, to appear.

DIVISION OF MECHANICAL ENGINEERING (NRC/DME)
SYSTEMS LABORATORY

Building M-3, Montreal Road
Ottawa, Ontario
K1A 0R6

Mr. P.A. Hamill
Head, Systems Laboratory
(613) 993-9208
Telex: 053-3386

I) Summary

DME's Systems Laboratory was established in 1982 by combining the Analysis Laboratory (Engineering System Modelling and Simulation Group) and the Control Systems and Human Engineering Laboratory (Process Control, Discrete System Simulation and Ergonomics). The centre's robotics activity is part of their Automation and Ergonomics project.

Key areas of specialization are: intelligent systems, advanced automation, and man/machine supervisory systems. Their research includes: off-line programming of industrial robots, intelligent control of sensor/robot systems, kinematics, dynamics, supervisory control of remote programmable manipulators, and artificial intelligence applications.

Current R&D efforts are the development of a self-calibrating robotics system using vision to locate the end-point of the robot, and AI development to allow "implicit" programing whereby the robot teaches itself most of the program routine.

The centre is equipped with a PUMA 560 interfaced to a VAX 11/780. A flexible robotics machining cell housing two CNC machines and an ASEA RB 60 robot is used for producing machine parts and theory development. Also in-house are a Lambda Plus artificial intelligence work station and a 3D non-contact optoelectronic displacement sensor hosted by a LSI 11/23 with a data acquisition rate capability of 10 KHz. Various force, tactile, proximity and low resolution vision sensors are in-house or on order.

The centre's clientele is Canadian industry. Its activity is aimed at high risk R&D for medium to long term industrial needs, and its future level of effort therefore depends on industrial needs and government priorities. Collaborative projects are preferred.

The Systems Laboratory group is small but it has access to the DME's resources and excellent industrial contacts. Its activity bridges the gap between such provincial centres as ORC and university research labs.

II) Additional Contacts

E.H. Dudgeon Director
H. Elzorkany Associate Research Officer (Control Systems)

III) Bibliography

1. Mufti, I.M., Control of manipulators, 1984.

2. CICS Conference, On the dynamic equations of manipulators, 1984.

3. Mufti, I.H., Equations of motion for rigid multibody systems, 1983.

4. Elzorkany, H.I., Basics of motion and control of robots, 1984.

5. Elzorkany, H.I., Robot programming, 1984.

6. DME, Automatic correction in off line programming of industrial robots, 1984.

ONTARIO HYDRO - RESEARCH DIVISION

800 Kipling Avenue
Toronto, Ontario
M8Z 5S4

Ms. A.C. McMillan
Special Projects Scientist
(416) 231-4111
Telex: 06-984706

I) Summary

Ontario Hydro has the largest utility research and development facility in Canada. It sees robots and robotic technology as a method to solve real-world problems within the utility industry.

A number of staff members work directly on robotic projects and also sub-contract work for Canadian firms. One of these firms is Spar Aerospace Ltd. which has developed and built a hydraulic robot which is capable of transporting a 2500 pound load, at a 40 foot reach, to within 0.1 inch of its target. This robot will be used for large-scale fuel channel replacement in Ontario Hydro's nuclear reactors. Other robotic projects are outlined below.

Robotics Concepts Testing:

A system which is under development at present uses a 6-axis industrial robot, for scanning an ultrasonic probe over complex geometric surfaces. An external computer has been interfaced to the robot allowing the transmission of position and velocity data and robot commands, thereby greatly improving the capability of the robot.

NDE Inspection

A robot-like computer controlled system is under development for inspecting pressure tubes ultrasonically. This system uses servomotors to drive an inspection head into a pressure tube of the nuclear reactor.

Robotic Welding

Research is progressing at the Ontario Hydro Research Laboratory into the use of robotic technology for welding repairs. The use of robotics for this kind of work is beneficial because it removes the worker from a hostile environment and reduces the exposure of personnel to radiation.

Another unique research project involves the use of holographic interferograms in the development of 3-D vision.

Ontario Hydro's intent is to cooperate with Ontario industry in order to transfer Hydro's technology to those industries.

ONTARIO ROBOTICS CENTRE (ORC)

743 Monaghan Road
Peterborough, Ontario
K9J 5K2

Mr. I.A. Barrie
Vice President and General Manager
(705) 876-1611

I) Summary

The Ontario Robotics Centre is a partially funded provincial corporation specializing in manufacturing engineering. It is one of six centres of advanced technology established by the Ontario government. Its particular mandate is to provide industry with professional advice and applications engineering on advanced, economically-justified manufacturing systems based on commercially available automation technology. All of its research is in the area of applications. ORC's main research activity is to liaise with Ontario manufacturing and research facilities, communicating industry requirements to the research centres.

One of the centre's major applied R&D accomplishments is the conceptual solution for the automated inspection of automative instrument panels employing vision systems, tactile sensors, and a robot.

Established in 1982, ORC has a staff of 27, with 65 contracts for consulting services secured in 1984/85 and 27 seminars presented, for a combined revenue of $1.2 million. Its clients, to date, include Ontario-based manufacturers in various industries, among them: the automotive, boating, consumer goods, food packaging, electronics, textiles and footwear industries. So far, the centre has promoted the installation of advanced manufacturing engineering systems in approximately thirty companies.

ORC's facilites in Peterborough house:

robots: Unimate 2570, Nordson NRS-11, Fanvs M-J, American Merlin, ASEA IRB 60/2, Cincinatti Milacron T3-746, Automatix, Martonair M/35, Schrader Bellows Motion Mate, Seiko M700

vision systems: 2 Automatix, Pattern Processing Technologies

CAD facilities: McAuto (3D), CAD facility (2D), AutoCAD (IBM)

simulation packages: PLACE, SEE WHY, Siman

computers: VAX 11/750, Digital office autmation system, 10 PCs

II) Additional Contacts

K. Jones	President
B. Durant	Manager - Educational Services
H. Lowe	Manager - Technical Services

M. Patrick	Manager - Applications Engineering
T. Spoore	Manager - Client Services

III) Bibliography

1) Hanright, John, Selecting your first arc welding robot, 1984.

2) Lowe, Harry, An integrated robot vision and tactile automation inspection system, 1984.

3) Pick, Clark, Animated computer graphics for factory and robotic workcell design - a user's perspective, 1984.

4) Szvoboda, Gabor, Employment and the human side of automation, 1984.

CENTRE DE RECHERCHE INDUSTRIELLE DU QUÉBEC (CRIQ)

333, rue Franquet
C.P. 9038
Sainte-Foy, Québec
G1V 4C7

Mr. G. Turp
Director of Robotics Research
(514) 694-3330
Telex: 051-31569

I) Summary

The CRIQ is a corporation of the Province of Quebec founded in 1968 to work with Quebec manufacturers in order to develop new products and processes, to upgrade production methods, to promote the transfer of technology, and to provide technical information services to the industrial community.

CRIQ's objective is to promote the implementation of existing robotics technology and does not plan to design robots unless contracted to do so. Among the applications it has developed are palletizing and die casting operations.

The Centre concentrates much of its R&D effort on machine vision and pattern recognition for general automation projects including sensors for robotics applications. Its achievement of pattern recognition for the identification of defects in fish fillets indicates the sophistication of CRIQ's R&D in that field.

CRIQ's clients are primarily small and medium sized companies. Technical information services are provided without cost to industry. R&D work, engineering consulting, and analysis are performed on a contract basis, with 550 contracts being carried out in fiscal 1983/84.

A new building of 135,000 square feet is scheduled for completion in October 1985. The Centre plans to hire an additional 135 R&D personnel in order to strengthen their capability in modern manufacturing technology, specifically, in their FMS and robotics efforts.

The facility houses robots: ASEA IRB L/6, IRI, Seiko, Armdroid, Microbot
Computers: 2 VAX 11/750's, VAX 785, HP 3000, PDP-11, IBM-PC's
and OKK 5 axis NC manufacturing equipment

CRIQ expects to share major achievements in systems engineering for robotics applications and CAD/CAM with the Ontario Centre for Advanced Manufacturing (OCAM) and with other centres interested in promoting the diffusion of knowledge.

II) Additional Contacts

C. Baronet	Vice President - Operations Montreal
J. Plourde	Vice President - Operations Quebec
H. Baumans	Director - Electronics, Computer Vision, Telecommunications
F. Dugal	Director - Materials
J.J. Dumas	Director - Automation, Industrial Engineering, Energy
M. Gagnon	FMS Specialist
F. Gauthier	Computer Vision, Patter Recognition
R. Larochelle	Director - Products Design, CAD, Mechanical Analysis
R. Lavoie	Director - Mechanical, Heavy Machinery, Forestry Equipment, CAD

4.2 Industrial Sector

The industrial sector is classified as, for the purposes of this report, the group of companies in private industry at which robotics R & D is performed. These companies are presented in the site entries which follow.

ROBOTIC SYSTEMS INTERNATIONAL

9865 W. Saanich Rd.
Sidney, British Columbia
V8L 3S1

Mr. J. Wilson
President
(604) 656-0101
Telex: 049-7292

I) Summary

RSI was incorporated in 1983 as a spin-off firm from International Submarine Engineering Ltd. (ISE). RSI assumed ISE's subsea remote manipulator technology and recently added microprocessed-based robot control systems to apply the manipulator technology in other hostile environments and in hazardous waste handling.

RSI's main R & D objectives are supervisory control of a man-in-the-loop robotic systems and 'tele-presence' (improved sensing technology). These aims involve them in sensor development, robot control architectures for tele-operator systems, high level online and offline robot programming languages, fault-tolerant systems, actuators, voice-controlled robotics, and ergonomics in man-machine systems. The company plans to continue its R & D effort in bilateral force feedback and on hazardous material handling.

The company has achieved the development of a new generation of tele-manipulators and concepts of master-slave control, robust sensors, and exceptional strength-weight ratios for their manipulator arms. As a follow-up to designing six-legged remotely-controlled robots for use in a movie, RSI has undertaken R & D in alternative walking strategies and implementation approaches under computer-controlled supervisory systems.

The typical R & D projects include the design and production of a robotic system for repair and maintenance of electrical live distribution lines; production of a robot and associated equipment to fuel US Navy Torpedos; a seven-function manipulator system for use on the Carnegie-Mellon University's Robot Excavation Systems; and remotely operated vehicles and manipulators for hazardous waste handling.

Company facilities include an 8,000 square foot plant where they manufacture manipulators and control systems. RSI have some in-house machining facilities and electrical and drafting departments. The premises house:

- a full-scale remotely operated hazardous material handling vehicle and manipulator
- a full-scale replica of a subsea vehicle front with operational robotic manipulator, camera pan, tilt units and voice control

The educational department contains three 'Excalibur' robots, a six-axis table model robot manipulator used for educational purposes in-house and at universities.

II) Other Contacts:

D. MacDonald	Vice President, Manager - Control Systems
B. Higgs	Manager - Education Robots
T. Peace	Manager - R & D
B. Ramsbottom	Manager - Remote Systems

III) Bibliography:

1. RSI Research and Development, IRAP Manarm Project, RSI, 1984.
2. Telepresence - Fact and Fantasy, RSI, 1984.
3. Subsea Manipulators, RSI, 1985.

HORIZON ROBOTICS SYSTEMS (CANADA) INC.

2502 Thayer Ave.
Saskatoon, Saskatchewan
S7L 5Y2

Mr. L.T. Oliver
Executive Vice President
(306) 934-1557

I) Summary

Horizon Robotics is an industrial robot company established in 1984 to offer consulting services to companies making the transition to advanced manufacturing techniques. Services offered include seminars, both in-house and on-site, as well as the direct consulting services of needs assessment, system planning, supplier liaison, and cost analysis. While it offers services to a broad spectrum of industry, it places emphasis on the agricultural field. Principle research goals are remote manipulation and automatic factory concepts, including gripper and wrist design.

The company has a 30,000 square foot plant including seminar rooms, a CAD/CAM area, a robotics library, and various training systems such as Motion Mate MMR1, Microbot Teachmovers, Control Data Workstations, and PC's. Expansion plans involve the acquisition of more robots and renovation of their CIM integration area. Horizon plans to develop a full CIM centre should the marketplace and advances in hardware and software warrant it.

Horizon is cooperative by design. It is currently active in negotiating with various firms to establish a Western Canada chapter of Robotics International and with the University of Saskatchewan, Department of Engineering, to develop joint research projects. The company has strong ties with several corporations including GCA, American Robot, and Schrader Bellows.

II) Other Contacts:

A. McElwee	President
B. Kirik	Facilities Manager
T. Muench	Applications Engineer

BATA ENGINEERING

Batawa, Ontario
K0K 1E0

Mr. B. Riden
V.P. & General Manager
(613) 398-6106

I) Summary:

Bata Engineering designs, manufacturers, and assembles machinery for the shoe industry. With a total staff of 400, including 240 engineers, and a first-class engineering and machine shop, Bata has been responsible for several major technological achievements including a programmable materials cutting table with a water knife, and a 3D CAD system for shoe design. Both of these items will be marketed. In the field of robotics R & D, they are developing a robotic arm, and may, in the near future, manufacture robotic assembly systems for industrial use.

CLAY-MILL TECHNICAL SYSTEMS INC.

2855 Deziel Drive
Windsor, Ontario
N8W 5A5

Mr. J.K. Arner
Vice President, Manufacturing
(519) 944-7902

I) Summary:

Clay-Mill began its operation in 1974 as X-Mation Tool Company and now builds specialized automative tooling and robotic systems for heavy duty applications. Its Windsor Ontario facility has been known by its present name since 1983 when Clay-Mill staff developed a strong, versatile gantry type industrial robot. The company proposes to produce a version of this robot and complimentary robotics systems for the automotive market, its main clientele. They have developed a rotating axis which gives the robot five degrees of freedom without affecting its lift capacity.

Research is planned in stress analysis, vibration, statistics, kinematics, dynamics, hydraulics, and strength. Their principal research objective is to perform a stress analysis on their robot to determine its design capacity.

The company's facilities include 30,000 square feet of manufacturing space. Clay-Mill has the technical and machine capacity to design and build complete automotive tooling and robotic systems in-house.

II) Other Contacts:

C. Pearce	Director - Engineering & Production
D. Pearce	General Counsel

CRS PLUS LTD.

P.O. Box 163, Station A
Burlington, Ontario
L7R 3Y2

Mr. R. Simmons
President
(416) 787-3642 Toronto
(416) 545-7207 Hamilton

I) Summary:

CRS Plus specializes in the application of microcomputers in industrial automation. Their research objective is the development of small, sophisticated robotic systems and they have developed a CNC controller and prototype teaching robot. Research areas include motion control, robot programming languages, interfacing, DC Servo systems, real-time control software, operating system software, and parallel processing. They have a small robot system in-house (the CRS-009), and IBM, Apple and Intel microcomputers.

II) Bibliography:

1. Rafauli, R., et al., A microprocessor control system for an industrial robot, 1981.
2. Rafauli, R., et al., A distributed microprocessor control system for an industrial robot, 1981.
3. Rafauli, R., et al., A continuous path algorithm for robot control, 1982.

DIFFRACTO LTD.

6360 Hawthorne Drive
Windsor, Ontario
N8T 1J9

Mr. T.R. Pryor
Chairman
(519) 945-6373
Telex: 06-477875

I) Summary:

Diffracto develops, builds and installs machine vision systems, including vision-based inspection robots. The company was established in 1973 through NRC funding and now has two facilities: a 70,000 square foot facility in Windsor, Ontario, and a 2,000 square foot facility in Troy, Michigan. Other sites are planned in Windsor, Quebec, and Winnipeg. Plans for expansion include a new robot guidance operation involving sixty R & D personnel within two years. A major expansion of their machine vision inspection operation in Windsor is in progress. Diffracto's clientele include: manufacturing the automobile industries, defence contractors, and the Canadian and US Military. It has close working ties with GM APMES, most GM and Ford plants, Hommelerke GmbH (Germany), DRIE, and NRC.

Apart from the inspection robots it builds, Diffracto has five robots for R & D purposes, a VAX 11-750, eight PDP-11/23 and Microvax systems, and a wide range of electro-optical equipment.

The company's main effort in robotics research is the development of inspection robots with machine vision sensors to inspect car body parts, turbine blades and gears. It is presently involved in a project with NRC and GM Canada based on the Canadarm guidance system. This joint effort is to develop machine-vision based dynamic robot controls for machine accuracy improvement, assembly, material handling, and off-line program verification. Other research interests include vehicular robots and military applications. Diffracto's total R & D effort since inception has involved $30 million. It has developed over 20 commercial products to date and holds over 100 patents.

II) Additional Contacts:

O. Mageniers	Vice President
W. Pastorius	Vice President - Marketing

MAGNA INTERNATIONAL INC.

Research and Development Centre
36 Apple Creek Blvd.
Markham, Ontario
L3R 4Y4

Mr. W.J. Schabereiter
Vice President, Special Projects
(416) 477-7766
Telex: 06-966856

I) Summary:

Magna developed a small robot for use in limited 'pick and place' applications in conjunction with automated equipment. The robot is a simple, inexpensive, programmable manipulator. Magna has not been involved in further research and development into robotics technology, and has no plans to commit funding to such activity unless, as in this case, the development evolves naturally from their main design efforts.

PROMATIC INTERNATIONAL LTD.

7518 Bath Road
Mississauga, Ontario
L4T 1L2

Mr. B.C. Millar
President
(416) 677-7991

I) Summary:

Promatic is a small company engaged in the development of manufacturing methods, some of which border on robotic methods and technology. Their field of specialty, however, is the development of standarized modular systems including work performing, parts moving and packaged controllers.

Their first series, the 50K is now complete, and a 30k series, smaller in component size, is under development. Both series comprise a group of air-driven, interrelated components which can be used individually or combined in various ways to perform a wide variety of industrial motions. The modules can be divided into two broad groups: the first consisting of modules based on a simple toggle or machine slide can designed to perform pressing, forming and drilling functions; the second consisting of material moving modules which can be built into robot-like devices. Most automatic machines built and supplied by Promatic use PC-based control systems.

While other companies provide modular automation for building robotic-type units, Promatic is unique in developing modular work-performing automation. Promatic expects to confine its R & D effort to products, specifically modules, suitable for manufacture and sale to industry. Model and prototype construction is performed in their machine shop.

II) Other Contacts:

K.W. Little — Vice President, Shop Supervisor

SPAR AEROSPACE LTD.
REMOTE MANIPULATOR SYSTEMS DIVISION (RMSD)

1700 Ormont Drive
Weston, Ontario
M9L 2W7

Mr. G. Norgate
Manager, Research & Development
(416) 745-9680
Telex: 065-27360

I) Summary:

The Remote Manipulator Systems Division of Spar was established in 1977 in response to the need to develop a remotely operated teleoperator system for the NASA Space Shuttle Orbiter. The result was a production unit manufactured and delivered for services known as the 'Canadarm'. The division has since been engaged in developing a teleoperator system for fuel tube replacement in CANDU nuclear reactors. RMSD's current R & D effort focuses on an integrated servicing system to be used on the U.S. Space Station.

The overall objective of RMSD is to combine state-of-the-art concepts and technologies in manipulator control, computer vision and artificial intelligence and prove their effectiveness in advanced teleoperator or robotic control systems. While the R & D facility is a major part of the Division's activity, it is not its prime function, that being to develop and then produce teleoperators for space and terrestrial applications. Research areas include resolved motion control, active compliance, trajectory planning, heuristic control, flexible structure control, robot control language, task knowledge representation, man-machine interface, and vision feedback. Major accomplishments include a real-time control line between the CM-T3 robot and the PE3200 host computer, interfacing a hand controller to the CM-T3, installation of a force/motion sensor on the CM-T3, and software standardization.

The company welcomes the opportunity for joint ventures and actively supports collaboration between industry and universities. It is presently involved the NRC and the Canadian Institute of Advanced Research (CIAR). Their clients include NRC, NASA, Ontario Hydro and DOC.

RMSD's facilities include:

- Cincinnati Milacron T3-776 Robot (CM-T3)
- Wrist-mounted force/moment sensor for the CM-T3
- PaR Model 3000 manipulator
- Perkin Elmer MPS 3200 computer
- Trapix 5500 real-time image processor
- Canadarm simulation facility

Air-bearing floor
Hand controllers (force feedback)

Spar plans to expand its RMSD facilities to include general purpose robotics test beds for component functions, and a general purpose man-in-loop real-time/non-real-time simulation facility.

II) Other Contacts:

P. Pickerill	Manager - Marketing, Industrial Systems
J. Stoumann	Senior Staff Engineer (Vision)
J. Yuan	Staff Engineer (Robotic Control)

III) Bibliography:

1. Norgate, G., AI: The future in nuclear plant maintenance, 1984.
2. Yuan, J. S-C., Active model control of flexible structures in application to space construction and servicing.

VADEKO INTERNATIONAL INC.

6535 Millcreek Drive, Unit #62
Mississauga, Ontario
L5N 2M2

Dr. G. Whitehead
President
(416) 821-3222
Telex: 065-28105

I) Summary:

Vadeko has grown to a staff of 55 since it was established in 1981 as a consulting company in the field of electro-mechanical system engineering. Their research objectives are product-oriented: the design and production of end-of-arm tooling and specialized multifingered grippers, and the design of robotic systems for commercial production. Other research areas include CAD/CAM, offline programming, and graphic simulation. Among their areas of specialty are hierarchical and adaptive controls, and realtime and operating software. Their research is directed towards applications in the subsea, nuclear, mining, and railways environments.

Vadeko offers services in the planning, design, installation, and commissioning of industrial robots. Their clients include the nuclear and railways sectors, the NRC and the Bank of Canada. Projects include the development of reactor maintenance equipment and a multi-robot paint system for the automobile industry. Vadeko is developing a large robotic system for the railway industry which will include downloading of programs to robots from a CAD system, specially designed software, hardware, and robots. The company is a System Application Centre for the Robot Products of Hitachi Ltd., offering training and product support.

Its facilities include a Hitachi robot, a Computervision CAD unit, a machinery workshop and electronics laboratory, a Hewlett Packard HP1000 computer, and ten personal computers. Vadeko has its own machine shop and applications workshop.

II) Additional Contacts:

Z. Hershtal	Vice President
C. Butt	Manager - Industrial Robot Systems
J. Gibson	Vice President - Finance & Administration
I. Grantmyre	Program Manager - Robotic Painting, Mining
J. Meseltine	Engineering Manager
G. Small	Program Manager - Software
J. Taylor	Consultant - Design

WELDING INSTITUTE OF CANADA (WIC)

391 Burnhamthorpe Road East
Oakville, Ontario
L6J 6C9

Dr. A.G. Glover
Director of Technology
(416) 845-9881

I) Summary:

The Welding Institute of Canada is a professional organization representing major metal fabricators, supply and service companies, oil and gas pipeline transmission organizations, power utilities, transportation companies, and many smaller companies involved in welding. The WIC conducts research activities in the NRC Industrial Materials Research Institute (IMRI) Laboratory in Boucherville, Quebec, where it is involved in welding automation R & D.

One of their research efforts concentrates on the adaptive control of such welding parameters as penetration through weld-pool monitoring with infrared technology.

The IMRI laboratory is perhaps the best-equipped welding laboratory in North America, containing computer and microprocessor-controlled systems and welding equipment including a large industrial welding robot.

The WIC offers technical assistance, research programs, and modular learning programs to its membership.

WESTINGHOUSE CANADA INC.

P.O. Box 510
120 King Street West
Hamilton, Ontario
L8N 3K2

Mr. B. Teal
Manager, Manufacturing Technology
(416) 522-8811

I) Summary:

Westinghouse Canada's Corporate Productivity Services houses five industrial robots. The centre conducts feasibility studies for applications of advanced technologies, including robotics, and has the capacity to simulate possible productivity improvements suggested by operating personnel. The centre is for the service of Westinghouse only, its mandate being to help the company achieve its targets in inventory, productivity, quality, and world competitiveness. It offers Westinghouse personnel awareness seminars on robotics, automated inspection, and robotic assembly workcells.

XENOTECH SYSTEMS INC.

101 Trillium Drive
Kitchener, Ontario
N2E 1W8

Mr. J.A. Ford
President
(519) 893-3730

I) Summary:

Xenotech is a subsidiary of Automation Tooling Systems (ATS) which has developed the X10 intelligent vision system, a binary system offering four levels of grey and menu-driven programming. It is the only vision system on the market that is controlled by personal computer, either IBM or Apple. Applications include inspection, robot control, gauging, character recognition, and bar code recognition. Because of its PC compatibility, the cost of the system is low (approximately $15,000).

II) Additional Contacts:

K. Woerner	President
G. Wooten	Vice President

SERVO-ROBOT INC.

1401 rue Graham Bell
Boucherville, Quebec
J4B 6A1

Mr. J.P. Boillot
President
(514) 655-4223
Telex: 05-267624

I) Summary:

Servo-Robot is a Montreal-based company established in 1983 to develop, manufacture and supply flexible manufacturing workcells for arc welding. R & D work presently represents the major portion of their activities.

The company is performing NRC-sponsored research to develop an intelligent vision system for robots. Servo-Robot shares an R & D program with CLOOS, a German corporation, and has exclusive North American distribution rights for CLOOS robotic welding systems.

Principal research objectives are the development of SERVO-ARC, a seam-tracking system for pulsed-MIG welding applications, an integrated vision system for arc welding robots, and an intelligent controller and programming system for welding robots. They have developed an artificial vision system based on laser triangulation. Research areas include adaptive control of the welding process employing infrared and solid state cameras in prototype systems for real-time joint tracking and weld pool control. Their research could be of value to other robotic areas where real-time control or artificial vision is required.

Servo-Robot facilities house two robots for arc welding R&D, a MOTOROLA development system, a vision system, electronic laboratory equipment, and machining, fabricating and welding equipment. Expansion plans include a new plant for the manufacture of robot peripheral equipment such as robotic positioners.

The company's market includes manufacturers in all fields involving welding operations. Servo-Robot specializes in technology transfer from national laboratories and universities.

II) Other Contacts:

A. Galibois	Vice President
F. Ferrie	Project Manager, Artificial Vision & Robots
J. Hamel	Director
P. Poillot	Director

III) Bibliography:

Numerous papers on artificial vision for robotic welding, adaptive welding systems, et al.

WELDING INSTITUTE OF CANADA - QUEBEC CENTRE

2401 rue de la Province
Longueuil, Quebec
J4G 1G3

Mr. B. Graville
Director, Program Development
(514) 651-5086
Telex: 055-61622

I) Summary

The Welding Institute of Canada is developing robots for welding, especially in the area of vision (seam tracking). The Institute is concentrating on infra-red sensing and acoustic sensing for control of welding.

The Institute's main research objectives address the area of computer technology application to the control of welding systems. Their major accomplishment to-date is the development, and demonstration, of a passive infra-red system for welding which includes seam tracking and heat input control.

The majority of the Welding Institute's work is devoted to industry and, at present, they have international clients.

II) Bibliography:

To be published:

1. Fafard, P., Boillot, J.P., Conception d'un controlôleur à micro-ordinateur dédié au soudage adaptatif, Institut International de la Soudure, 1985.

Publications:

1. Boillot, J.P., Cielo, P. Bégin, G., Michel, C., Lessard, M., Fafard, P., Villemure, D., Adaptive welding by fiber-optic thermographic sensing, 1983.

2. Boillot, J.P., Bégin, G., Real-time adaptive welding systems, Conference Welding in Energy Related Projects, September 20-21, 1983.

3. Boillot, J.P., Bégin, G., IR vision applied to adaptive welding, 97e Congrès de l'Institut Canadien des Ingénieurs, April 25-27, 1983.

4. Boillot, J.P., Bégin, G., Welding adaptive functions performed through infrared (IR) simplified vision scheme, SPIE, Robot Vision and Sensory Control, Nov. 7-10, 1983.

5.0 CONCLUSIONS AND CLOSING REMARKS

The index and guide to robotics research and development in Canada is the product of an investigation of work performed in Universities and industry. The guide provides basic information on the activities of various centers to facilitate future communication between individuals and groups of researchers from both within Canada and abroad.

The investigation performed by the team from the University of Toronto and the Ontario Robotics Centre has revealed: i) a tremendous interest in research and development in this area; ii) several centers with a strong history of research; and iii) many more centers in the process of building a program of research in this area.

In general, the quantity and quality of work being conducted across Canada is impressive. More importantly, the potential which exists at some centers is considerable.

The methodology of obtaining the information and preparing the guide is considered adequate considering the constraints set forth by the National Research Council. The short duration of the study is the major factor responsible for any omissions and possible misinterpretation that may exist. However, it should be emphasized that many centers have not responded at all, or have responded to the questionnaire without the underlying concern for accuracy and completeness of information. The team has made every effort possible to ensure that the material presented reflects the best and most complete set of the information that was provided.

During the course of the study it was made clear that the purpose of this investigation was to document facts rather than evaluate work. However, the team has indicated, at least globally, which centers lead in the field and which centers have potential for growth. The major concern is that, in some cases, the work performed is not justified by the existing human resources, funding or need. In particular, it was felt that awareness of work performed in the U.S.A., Japan, and Europe must be increased to avoid situations where work already performed elsewhere is "reperformed". In addition, it should be emphasized that more publications are necessary to increase the "Canadian content" in international journals.

In general, it was felt that, except for some selected centers, the level of funding is not adequate. This area of research is of vital importance to the country, and it should be supported accordingly. This comment refers to government granting agencies, industry and research centers. The research community must reach out and communicate ideas in order to ensure awareness and support. On the other hand, a long term perspective for research and funding is a necessary condition for growth in this area. The government granting agencies must play a significant role in this regard.

REFERENCES

1. Aleksander, I., (consultant editor), Directory of world research and development activities, The International Robotics Yearbook, Kogan Page Ltd., London, England, pp. 229-233, c1983.

2. Manning, E., Cerone, N., Holt, R., Mylopoulos, J., Vaucher, J., Towards a Canadian fifth generation research plan, Canadian society for fifth generation research, draft 3, November 28, 1984.

3. McCalla, G., Cercone, N., CSCSI/CSEIO directions for Canadian artificial intelligence, February 27, 1984.

4. SME Directory of Robotics Education and Training Institutions in Colleges, Universities and Technical Institute, Dearborn, Michigan, April 1984.

6. Commonwealth Universities Yearbook 1983, Association of Commonwealth Universities, Vol. 2, C-H, pp. 832-1303.

7. Birk, J.R., Kelley, R.B., An overview of the basic research needed to advance the state of knowledge in robotics, IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-11, No. 8, pp. 574-579, August 1981.

8. Book, W.J., A perspective on robotics research and this issue, Transaction of the ASME, Journal of Dynamic Systems, Measurement and Control, Vol. 102, pp. 106-107, June 1981.

9. Schreiber, R.R., (staff editor), Research in robotics: Some critical issues, Robotics Today, pp. 66-71, August 1984.

10. Reid, K.N., Cohen, R., Garrett, R.E., Robins, M.D., Winer, W.O., Research needs in mechanical systems, Mechanical Engineering, pp. 29-43, March 1984.

11. Goldenberg, A.A., and staff, Proposal for an index and guide to robotics research and development in Canada, submitted to NRC, October 1984.

APPENDIX A

"An Index and Guide to Robotics Research and Development in Canada"

Questionnaire

University of Toronto
Department of
Mechanical Engineering

5 King's College Road,
Toronto, Ontario, Canada,
M5S 1A4

RE: Guide to Robotics R&D in Canada

As explained in the accompanying notice from the National Research Council, our Robotics and Automation Laboratory has been selected to develop a guide to robotics research and development in Canada.

Recognizing the nature of robotics R&D and the nature of the intended report, the information required will be obtained, where possible, by direct visits to the research locations. In other instances, and even where direct visits are appropriate, the enclosed questionnaire will form an efficient basis for recording and gathering the necessary information and presenting it in a coherent form. In most instances, the information requested is believed to exist in a readily available form, such as supplementary reports, brochures, etc. which will facilitate questionnaire responses. We urge all concerned to devote the small amount of time necessary in consideration of the benefit which will result. It is intended that each participating organization will receive a copy of the resulting report.

The importance of this project cannot be overstated. In order to increase our research community's awareness of national robotic developments and to increase international awareness of Canadian developments and capability, an intensive guide to robotics research and development within Canada is required. This guide will be a valuable reference to both the Canadian and international communities interested in integrating research developments. In addition, the guide would aid in the selection of future research areas. For the international community, the robotics research and development guide will clearly define the direction and extent of robotics research within Canada and will illustrate the advanced capabilities which we, as a nation, possess.

Bearing in mind the importance of the data which you are asked to provide, I once again ask that you devote an appropriate amount of time to completing the attached questionnaire.

Should you have any comments or questions, please feel free to contact me at (416) 978-3049. Thank you for your time in this matter.

Sincerely,

Andrew A. Goldenberg
Associate Professor
Robotics and Automation Laboratory Head

AAG/fq
Enclosure

National Research Council Canada
Conseil national de recherches Canada

Institute for Manufacturing Technology
Institut de technologie en production industrielle

Ottawa, Canada
K1A 0R6

Guide to Robotics R&D in Canada

Recognizing the potential for the application of robotics technology in a wide range of functions and services, there is a need to develop a guide to robotics research and development in Canada as a readily available document or report. This report will be useful in a number of ways such as follows:

- The report will be of value to researchers in universities, government laboratories, industry and elsewhere in planning their on-going work and in using to maximum advantage the work of others.

- Canada is one of a number of countries participating in the Joint Coordinating Forum on International Cooperation in Advanced Robotics. The main purpose of this forum is to facilitate, through international cooperation, the development of advanced robotic systems for applications which will reduce the necessity for people to work in harsh, difficult or dangerous environments. Accordingly, the guide to robotics research and development in Canada will be useful in informing officials and researchers in other participating countries of the interest and capability which exist in Canada and in arranging, where appropriate, Canadian participation in the joint projects which are currently in the planning stage.

- The report will be a useful reference and guide to managers and technical personnel in industry who have a need to know the locations where robotics R&D is being undertaken in Canada plus the nature and level of the work.

Accordingly, proposals were invited by NRC and arrangements subsequently made for members of the Department of Mechanical Engineering at the University of Toronto to gather the necessary information and prepare the text for a report which will be produced by the National Research Council as 'An Index and Guide to Robotics Research and Development in Canada'.

The assistance of those contacted in this project, and as described further in the accompanying letter, is encouraged and will be gratefully received. Please address your reply directly to the University of Toronto, as indicated, who will consolidate and organize the information into report form before printing by NRC.

Canada

AN INDEX AND GUIDE TO

ROBOTICS RESEARCH AND DEVELOPMENT IN CANADA

Questionnaire

Please print or type your answers, and return this questionnaire within the next two weeks to:

Robotics Research Guide
Dr. A.A. Goldenberg
Associate Professor
Department of Mechanical Engineering
University of Toronto
5 King's College Road
TORONTO, Ontario
M5S 1A4

Please attach any documents which will help explain the various aspects of your Centre. Such documents may include, for example, an annual report, other reports, brochures, data sheets, a statement of objectives or mission, a summary of products and services, etc.

Please feel free to answer specific questions in this questionnaire by making specific reference (including page number) to any such attached document which answers the question in a clear and concise way.

If for some reason, a particular question cannot be answered, please return the questionnaire regardless, with as many questions answered as possible. While participation in this collective undertaking is voluntary, we hope that as many organizations as possible will participate to the fullest extent possible and wish to thank all concerned for their assistance and co-operation.

The attached information is provided for use in the proposed NRC publication "An Index and Guide to Robotics Research and Development in Canada'.

Signed: _____

Name: _____

Title: _____

AN INDEX AND GUIDE TO

ROBOTICS RESEARCH AND DEVELOPMENT IN CANADA

Questionnaire: (Please refer to Appendix A before proceeding)

PART I: CENTRE DATA

Name of centre: _____

Postal address: _____

Telephone: _____ Telex: _____

Date of establishment: _____

1) Centre's history and growth:

_____

_____

_____

_____

_____

_____

2) Facilities (robots, computers, manufacturing equipment, etc.):

_____

_____

_____

_____

_____

_____

3) Affiliation(s):

4) Source(s) and amount of funding:

Source	Amount

5) Fee structure (if any), for external services, if such are provided:

6) Clientele:

7) Plans for expansion (if any):

PART II: STAFF DATA

8) Number of employees: _____

9) Names and titles of principal personnel (i.e. directors, full-time researchers, etc.):

Name	Title	Specialization

10) Names and titles of associated personnel (i.e. part-time researchers, regular subcontractors, etc.):

Name	Title	Specialization

PART III: RESEARCH ACTIVITIES

11) **Research areas:**

12) **Principal research objectives and/or directions:**

13) **Areas of specialization:**

14) **Major accomplishments/developments to date:**

15) A listing of major software programs either developed or used extensively in the research program:

16) A short list or indication of the other groups or clientele with whom the group most closely relates and communicates:

17) Complete bibliography of reports and papers. (Please indicate which have been published or submitted for publication and any others which are available for distribution to other interested R&D centres):

18) Where available and convenient, please enclose descriptive literature describing your centre or activities, reports available, recently published papers, special publications or other documentation:

PART IV: ASSESSMENT OF RESEARCH CAPABILITIES

19) **Please describe how your centre or activities fit into the overall Canadian research community dealing with robotics research and development. Please describe how your research is expected to be of assistance to others:**

20) **Canada is one of a number of countries participating in the Joint Co-ordinating Forum on International Co-operation in Advanced Robotics.** To what extent do you expect or anticipate that your centre or activities could participate in the joint projects arising from this forum and what research projects would you like to become involved in?**

** **See Appendix B**

APPENDIX A

SUGGESTED AREAS TO BE ADDRESSED WHEN CONSIDERING ROBOTICS RESEARCH AND DEVELOPMENT

The field of robotics research encompasses many engineering and applied science disciplines primarily in computer science and mechanical and electrical engineering. In an attempt to filter the more relevant material (i.e. important advances and state-of-the-art applications) and provide a systematic method of classification, the following areas should be specifically addressed:

Representation/Modeling

- knowledge representation
- world modeling
- learning

Control

- trajectory, planning and control
- kinematic modeling and control
- dynamic modeling and control
- hierarchical control
- co-operative control
- compliance, flexible structures
- kinematic redundancy
- collison avoidance
- fault-tolerance
- optimal control
- adaptive control

Sensors (contact and non-contact)

- pattern recognition (image enhancement and feature extraction)
- sensor development (hardware and software)
- interface
- range, resolution, accuracy

Man-Machine Interface

- remote manipulation
- teaching methods
- languages
- off-line programming and graphic simulation

System Architecture

- parallel processing
- real-time control software
- operating systems software

Gripper and Wrist Design

- compliant wrists
- multifingered hands
- instrumented wrists
- grippers for special applications

Robot Design

- materials
- optimization of work envelopes
- light weight
- dedicated and specialized hardware
- optimization of robot structure

Actuators

- hardware developments
- optimal design
- repeatability, resolution, accuracy

Locomotion

- mobility
- hardware developments

CAD/CAM - Robotics Interface

- software developments
- hardware developments
- automatic factory concepts
- graphic simulation

Applications

- manufacturing, precision assembly
- welding
- inspection and maintenance
- nuclear environments
- space environments
- underwater environments
- agriculture environments
- construction environments
- mining environments
- domestic services environments
- military applications

APPENDIX B

BACKGROUND ON THE JOINT CO-ORDINATING FORUM ON INTERNATIONAL CO-OPERATION IN ADVANCED ROBOTICS

To date, the forum has identified advanced robotic applications in space, ocean, nuclear, mining, agriculture, civil engineering, plant maintenance, fire fighting and rescue operations and services for planning and consideration. Similarly, key technology areas for development, in approximate order of need or priority, are: system architecture, intelligence, sensors, manipulation, man/machine systems, locomotion and actuators.

Based on their own integrated research efforts, countries are preparing to conduct the following co-operative activities:

- Exchange of data/information, researchers/study missions (including workshops and joint site studies at appropriate centres) on the R&D activities for advanced robot systems.

- Suggestions for common standards (robot components, interfaces, communication and languages).

- Establishment of common criteria for evaluation.

- Joint evaluation of technical aspects and joint experiments.

Countries currently involved as members are France and Japan (co-leaders), U.S.A., U.K., Germany, Italy and Canada plus the Commission of European Communities, Austria, Norway and the Netherlands as observers.

APPENDIX B

Sites Contacted

(Universities, Colleges, Government & Industrial)

Post-Secondary Educational Institutes

Listed in the pages which follow, in alphabetical order, are the university and college sites which were contacted in the course of producing the Index and Guide. In addition to indicating the name and address of the contact, the list entry indicates whether a response was received and if it was entered into the Index and Guide. Responses which were received but not entered (i.e., "response not entered") had either an insufficient level of robotics activity at this time (as indicated by respondent) or R & D activity which was not robotics-related (i.e., non-robotic CAD/CAM, AI). Of 54 questionnaire packages sent to 27 universities and five colleges, 49 responses were received; of these, 39 appear in the Index and Guide.

Universities (R & D Centres)

1. Alberta, University of (403) 432-4712
Department of Mechanical Engineering
Edmonton, Alberta
T6G 2E5

Attention: Prof. R. W. Toogood
(Response entered)

2. Alberta, University of (403) 432-5330
Department of Psychology
P220 Biological Sciences Bldg.
Edmonton, Alberta
T6G 2E9

Attention: Prof. T. M. Caelli
(Response entered)

3. Alberta, University of (403) 432-3359
Department of Physiology
7-55 Medical Sciences Bldg.
Edmonton, Alberta
T6G 2H7

Attention: Dr. R. B. Stein
(Response not entered - insufficient activity)

4. British Columbia, University of (604) 228-4902
Department of Mechanical Engineering
2324 Main Mall
Vancouver, British Columbia
V6T 1W5

Attention: Prof. D. B. Cherchas
(Response entered)

5. British Columbia, University of (604) 228-5934
Department of Electrical Engineering
2356 Main Mall
Vancouver, British Columbia
V6T 1W5

Attention: Prof. P. D. Lawrence
(Response entered)

6. British Columbia, University of (604) 228-3061
Department of Computer Science
6356 Agricultural Road
Vancouver, British Columbia
V6T 1W5

Attention: Prof. R. J. Woodham
(Response entered)

7. Calgary, University of (403) 284-5771
Department of Mechanical Engineering
2500 University Drive N.W.
Calgary, Alberta
T2N 1N4

Attention: Prof. E. C. Mikulcik
(Response not entered - insufficient activity)

8. Calgary, University of (403) 284-6015
Department of Computer Science
2500 University Drive N.W.
Calgary, Alberta
T2N 1N4

Attention: Prof. J. R. Parker
(Response entered)

9. Carleton University (613) 231-2634
Department of Mechanical/Aeronautical Engineering
Ottawa, Ontario
K1S 5B6

Attention: Prof. J. Z. Sasiadek
(Response entered)

10. Carlton University (613) 231-7545
School of Computer Science
Ottawa, Ontario
K1S 5B6

Attention: Prof. J. Oommen
(Response entered)

11. Carleton University (613) 231-3627
Centre for Advanced Studies in
Computer Aided Design & Engineering
Ottawa, Ontario
K1S 5B6

Attention: Prof. J. A. Goldak
(Response entered)

12. Concordia University (514) 879-4552
Department of Mechanical Engineering
SGW Campus - Annex B
1455 de Maisonneuve Blvd. W.
Montreal, Quebec
H3G 1M8

Attention: Prof. R. M. H. Cheng
(Response entered)

13. École Polytechnique (514) 340-4861
University of Montreal
Department of Mechanical Engineering
P. O. Box 6079, Station A
Montreal, Quebec
H3C 3A7

Attention: Prof. R. Baldur
(Response entered)

14. École Polytechnique (514) 340-4552
University of Montreal
Department of Electrical Engineering
Montreal, Quebec
H3C 3A7

Attention: Prof. R. Desantis
(Response entered)

15. Laval University (418) 656-2199
Department of Mechanical Engineering
Sainte-Foy, Quebec
G1K 7P4

Attention: Prof. M. Richard
(Response not received)

16. Manitoba, University of (204) 474-9535
Department of Mechnical/Industrial Engineering 474-9803
Winnipeg, Manitoba
R3T 2N2

Attention: Prof. O. Hawaleshka
(Response entered)

17. Manitoba, University of
Department of Electrical Engineering
Winnipeg, Manitoba
R3T 2N2

(204) 474-8380

Attention: Dr. S. Onyshko
(Response not entered - insufficient activity)

18. McGill University
Department of Mechanical Engineering
817 Sherbrooke St. W.
Montreal, Quebec
H3A 2K6

(514) 392-5480
392-5461
Telex: 052-68510

Attention: Prof. P. J. Zsombor-Murray
(Response entered)

19. McGill University
Department of Electrical Engineering
3480 University Street
Montreal, Quebec
H3A 2A7

(514) 392-5396
Telex: 052-68510

Attention: Prof. M. D. Levine
(Response entered)

20. McMaster University
Department of Mechanical Engineering
1280 Main St. W.
Hamilton, Ontario

(416) 525-9140
Telex: 061-8347

Attention: Prof. H. A. ElMaraghy
(Response entered)

21. Memorial University
Faculty of Engineering
St. John's, Newfoundland
A1B 3X5

(709) 737 8810
Telex: 016-4101

Attention: Dr. G.R. Peters, Dean
(Response not entered - insufficient activity)

22. Moncton, University of (506) 858-4309
Faculty of Science & Engineering
Moncton, New Brunswick
E1A 3E9

Attention: Prof. M. S. Eid
(Response not entered - insufficient activity)

23. Montreal, University of (514) 343-7090
Department d'IRO
C.P. 6128
Montreal, Quebec
H3C 3J7

Attention: Prof. N. F. Stewart, Chairman
(Response entered)

24. New Brunswick, University of (506) 453-4513
Faculty of Engineering Telex: 014-46202
P. O. Box 4400
Fredericton, New Brunswick
E3B 5A3

Attention: Prof. D. J. Bonham, Chairman
(Response entered)

25. Nova Scotia, Technical University of (902) 429-8300
Department of Mechanical Engineering Telex: 019-21566
P. O. Box 1000
Halifax, Nova Scotia
B3J 2X4

Attention: Dr. M. R. Kujath
(Response entered)

26. Nova Scotia, Technical University of (902) 429-8300
Department of Industrial Engineering Telex: 019-21566
P. O. Box 1000
Halifax, Nova Scotia
B3J 2X4

Attention: Prof. A. Kusiak
(Response entered)

27. Ottawa, University of (613) 231-3246
Department of Mechanical Engineering
Ottawa, Ontario
K1N 6N5

Attention: Dr. Redekop
(Response not received)

28. Queen's University (613) 547-2878
Department of Electrical Engineering
Kingston, Ontario
K7L 3N6

Attention: Prof. M. M. Bayoumi
(Response entered)

29. Queen's University (613) 547-6195
Department of Computing & Information Science
Kingston, Ontario
K7L 3N6

Attention: Prof. R. Browse
(Response entered)

30. Québec à Trois-Rivières, Université du (819) 376-5011
Département d'Ingénierie
C.P. 500
Trois-Rivières, Québec
G9A 5H7

Attention: Prof. K. Ghosh
(Response entered)

31. Québec à Trois Rivières, Université du (819) 376 5011
Département d'Ingénierie - Industriel
C.P. 500
Trois-Rivières, Québec
G9A 5H7

Attention: Prof. B. Montreuil
(Response not entered - CAD/CAM)

32. Saskatchewan, University of
Department of Electrical Engineering
Saskatoon, Saskatchewan
S7N 0W0

(306) 966-5379

Attention: Prof. H. C. Wood
(Response entered)

33. Saskatchewan, University of
Department of Computational Science
Saskatoon, Saskatchewan
S7N 0W0

(306) 966-4902

Attention: Dr. G. McCalla
(Response not entered - AI)

34. Sherbrooke, Université de
Department of Mechanical Engineering
2500 Université blvd.
Sherbrooke, Quebec
J1K 2R1

(819) 821-7160
Telex: 05-836149

Attention: Prof. M. Brezina
(Response entered)

35. Simon Fraser University
Faculty of Engineering Science
Burnaby, British Columbia
V5A 1S6

(604) 291-4371

Attention: Prof. T. McGeer
(Response entered)

36. Simon Fraser University
Department of Computer Science
Burnaby, British Columbia
V5A 1S6

(604) 291-4277

Attention: Dr. B. V. Funt
(Response entered)

37. Technologie Supérieure, École de
Université du Québec
Département de Mécanique
180 est, rue Ste-Catherine
Montréal, Quebec
H2X 1K9

(514) 397-3653

Attention: Dr. S. Lequoc
(Response entered)

38. Technologie Supérieure, École de
Université du Quebec
180 est, rue Ste-Catherine
Montréal, Québec
H2X 1K9

(514) 397-3664

Attention: Dr. E. Boridy
(Response not received)

39. Technologie Supérieure, École de
Université du Québec
Department of Automated Production
180 est, rue Ste-Catherine
Montréal, Québec
H2X 1K9

(514) 397-3629

Attention: Prof. J. Bouchard, Director
(Response entered)

40. Toronto, University of
Department of Mechanical Engineering
5 King's College Road
Toronto, Ontario
M5S 1A4

(416) 978-3049
978-6806
Telex: 06-218915

Attention: Dr. A. A. Goldenberg
(Response entered)

41. Toronto, University of
Department of Electrical Engineering
10 King's College Road
Toronto, Ontario
M5S 1A4

(416) 978-6341

Attention: Prof. H. W. Smith
(Response entered)

42. Toronto, University of (416) 978-6421
Department of Industrial Engineering
4 Taddle Creek Road
Toronto, Ontario
M5S 1A5

Attention: Prof. E. E. Pickett
(Response entered)

43. Toronto, University of (416) 978-6025
Department of Computer Science
10 King's College Road
Toronto, Ontario
M5S 1A4

Attention: Ms. J. Mager
(Response entered)

44. Toronto Western Hospital (416) 369-5030
Canadian Institute for Advanced Research
c/o Playfair Neuroscience
Rm. #903 North
399 Bathurst
Toronto, Ontario
M5T 2S8

Attention: Ms. D. Oki
(Response not received)

45. Victoria, University of (604) 721-8610
P. O. Box 1700
Victoria, British Columbia
V8W 2Y2

Attention: Dr. G. W. Vickers
(Response not received)

46. Waterloo, University of (519) 885 1211
Department of Systems Design Engineering Telex 069-55259
Waterloo, Ontario
N2I 3G1

Attention: Prof. A.K.C. Wong
(Response entered)

47. Western Ontario, University of (519) 679-3894
Faculty of Engineering Science
London, Ontario
N6A 5B9

Attention: Prof. J. A. MacDonald
(Response entered)

48. Western Ontario, University of (519) 679 2461
Department of Psychology
London, Ontario
N6A 3K7

Attention: Prof. Z. Pylyshyn
(Response not entered - insufficient activity)

49. Windsor, University of (519) 253-4232
Department of Mechanical Engineering
Windsor, Ontario
N9B 3P4

Attention: Dr. W. North
(Response not received)

Colleges (Training Centres)

50. Algonquin College (613) 598-3303
School of Technology
200 Lees Avenue
Ottawa, Ontario
K1S 0C5

Attention: Mr. C.N. Tite, Coordinator,
Manufacturing Engineering Technology
(Response entered)

51. Centennial College of Applied Arts & Technology (416) 752-4444
P.O. Box 631, Station A
Scarborough, Ontario
M1K 5E9

Attention: Mr. N.G. Eley, Dean, T.I.P.T. Division
(Response entered)

52. Ryerson Polytechnical Institute (416) 979-5106
Centre for Advanced Technology Education
350 Victoria St.
Toronto, Ontario
M5B 2K3

Attention: Mr. D. Hall, Managing Director, CATE
(Response entered)

53. Seneca College of Applied Arts & Technology (416) 591-5050
1750 Finch Ave. East Telex: 06-966659
North York, Ontario
M2J 2X5

Attention: Dr. D.E. Coates, Chairman, Mechanical Engineering
(Response entered)

54. St. Clair College (519) 966-1656
2000 Talbot Road
Windsor, Ontario
N9A 1S4

Attention: Mr. K.A. Brown, Program Coordinator
(Response not entered - no robotics)

Government and Industrial Sites

Listed in the pages which follow, in alphabetical order, are the government and industrial sites which were contacted in the course of producing the Index and Guide. The persons listed as contacts are either those to which the questionnaire was addressed or those who actually produced the response. As can be seen from the list, of the 31 sites contacted, 23 responded and were entered into the Index and Guide.

1. **Alberta Research Council** (403) 438-1555
Industrial & Engineering Research Division
Industrial Development Department
4th Floor, Terrace Plaza
4445 Calgary Trail South
Edmonton, Alberta
T6H 5R7

Attention: Mr. C. Harrison, Industrial Technology Advisor
(Response entered)

2. **Atomic Energy of Canada Ltd.** (613) 584-3311
Chalk River Nuclear Laboratories Telex: 053-34555
Chalk River, Ontario
K0J 1J0

Attention: Mr. N. Smith, Manager, Research Contracts
(Response entered)

3. **Bata Engineering** (613) 398-6106
Batawa, Ontario
K0K 1E0

Attention: Mr. B. Riden, Vice President & General Manager
(Response entered)

4. **Centre de recherche industrielle du Québec** (514) 694-3330
333 rue Franquet Telex: 051-31569
C.P. 9038
Sainte-Foy, Québec
G1V 4C7

Attention: Mr. G. Turp, Director of Robotics Research
(Response entered)

5. **Clay-Mill Technical Systems Inc.** (519) 944-7902
2855 Deziel Drive
Windsor, Ontario
N8W 5A5

Attention: Mr. J.K. Arner, Vice President, Manufacturing
(Response entered)

6. CRS Plus Ltd. (416) 787-3642
P.O. Box 163, Station A
Burlington, Ontario
L7R 3Y2

Attention: Mr. R. Simmons, President
(Response entered)

7. Diffracto Ltd. (519) 945-6373
6360 Hawthorne Drive Telex: 06477875
Windsor, Ontario
N8T 1J9

Attention: Mr. T.R. Pryor, Chairman
(Response entered)

8. Energy Mines and Resources Canada (613) 995-4059
Canada Centre for Mineral and Energy Technology
555 Booth Street
Ottawa, Ontario
K1A 0G1

Attention: Mr. R.T. Blake, Mineral Technology Information Officer
(Response entered)

9. Horizon Robotics Systems (Canada) Inc. (306) 934-1557
2502 Thayor Avenue
Saskatoon, Saskatchewan
S7L 5Y2

Attention: Mr. L.T. Oliver, Executive Vice-President
(Response entered)

10. International Nickel Company (705) 682-5210
Sudbury, Ontario
P0M 1N0

Attention: Mr. E. Kossatz, Vice-President, Mining
(Response not received)

11. Magna International Inc. (416) 477-7766
Research and Development Centre Telex: 06-966856
36 Apple Creek Blvd.
Markham, Ontario
L3R 4Y4

Attention: Mr. W.J. Schabereiter, Vice President, Special Projects
(Response entered)

12. National Defence, Department of (613) 992-5704
101 Colonel By Drive
Ottawa, Ontario
K1A 0K2

Attention: Dr. F.A. Payne, Directorate Research & Development Marine
(Response not received)

13. National Research Council of Canada (613) 993-0261
Division of Electrical Engineering Telex: 053-4134
Building M-50, Montreal Road
Ottawa, Ontario
K1A 0R8

Attention: Dr. J.Y. Wong, Director
(Response entered)

14. National Research Council of Canada (613) 993-9208
Division of Mechanical Engineering, Systems Laboratory Telex: 053-3386
Building M-3, Montreal Road
Ottawa, Ontario
K1A 0R6

Attention: Mr. P.A. Hamill, Head, Systems Laboratory
(Response entered)

15. National Research Council of Canada (514) 641-2280
Industrial Materials Research Institute
75 De Mortagne Blvd.
Boucherville, Quebec
J4B 6Y4

Attention: Mr. G.L. Bata, Director
(Response not received)

16. National Research Council of Canada (613) 993-9010
Institute for Manufacturing Technology
Building M-16, Montreal Road
Ottawa, Ontario
K1A 0R6

Attention: Mr. A. Mayman, Director
(Response not received)

17. National Research Council of Canada (613) 993-2427
National Aeronautical Establishment
Building M-60, Montreal Road
Ottawa, Ontario
K1A 0R6

Attention: Dr. G.M. Lindberg, Director
(Response entered)

18. Northern Telecom Ltd. (416) 275-0960
33 City Centre Drive
Mississauga, Ontario
L5B 3A2

Attention: Mr. D. Bowles, Director, Flexible Manufacturing Systems
(Response not received)

19. Ontario Hydro - Research Division (416) 231-4111
800 Kipling Ave., Room #KR295
Toronto, Ontario
M8Z 5S4

Attention: Ms. A.C. McMillan, Special Projects Scientist
(Response entered)

20. Ontario Robotics Centre (705) 876-1611
743 Monaghan Road
Peterborough, Ontario
K9J 5K2

Attention: Mr. I.A. Barrie, Vice President & General Manager
(Response entered)

21. Ontario Science Centre (416) 429-4100
770 Don Mills Road
Don Mills, Ontario
M3C 1T3

Attention: Dr. E. Mendis, Chief Scientist
(Response not received)

22. Pedsco (Canada) Limited (416) 755-3852
12 Principal Road, Unit #2
Scarborough, Ontario
M1R 4Z3

Attention: Mr. B. Pederson, President
(Response not received)

23. Promatic International Ltd. (416) 677-7991
7518 Bath Road
Mississauga, Ontario
L4T 1L2

Attention: Mr. B.C. Millar, President
(Response entered)

24. Robotics International of SME (416) 451-9150
c/o Mr. J. Dransfield
Northern Telecom Ltd.
8200 Dixie Road
Brampton, Ontario
L6T 4B8

(Response not received)

25. Robotic Systems International Ltd. (640) 656-0101
9865 W. Saanich Road Telex: 049-7292
Sidney, British Columbia
V8L 3S1

Attention: Mr. J. Wilson, President
(Response entered)

26. Servo Robot Inc. (514) 655-4223
1401 rue Graham Bell Telex: 05-267624
Boucherville, Quebec
J4B 6A1

Attention: Mr. J.P. Boillot, President
(Response entered)

27. Spar Aerospace Ltd. (416) 745-9680
Remote Manipulator Systems Division Telex: 065-27360
1700 Ormont Drive
Weston, Ontario
M9L 2W7

Attention: Mr. G. Norgate, Manager - Research & Development
(Response entered)

28. Vadeko International Inc. (416) 821-3222
6535 Millcreek Drive, Unit #62 Telex: 065-28105
Mississauga, Ontario
L5N 2M2

Attention: Dr. G. Whitehead, President
(Response entered)

29. Welding Institute of Canada (416) 845-9881
391 Burnhamthorpe Road East
Oakville, Ontario
L6J 6C9

Attention: Dr. A.G. Glover, Director of Technology
(Response entered see also entry for Quebec Centre)

30. Westinghouse Canada Inc. (416) 522-8811
P.O. Box 510
120 King Street West
Hamilton, Ontario
L8N 3K2

Attention: Mr. B. Teal, Manager, Manufacturing Technology
(Response entered)

31. Xenotech Systems Inc. (519) 893-3730
101 Trillium Drive
Kitchener, Ontario
N2E 1W8

Attention: Mr. J.A. Ford
(Response entered)